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MINUTES OF NINTH MEETING
of
NASA
RESEARCH AND TECHNOLOGY ADVISORY PANEL
ON
MATERIALS FOR AIRCRAFT ENGINES

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NINTH MEETING OF NASA RESEARCH AND
TECHNOLOGY ADVISORY PANEL ON
MATERIALS FOR AIRCRAFT ENGINES
(NASA) 82 p

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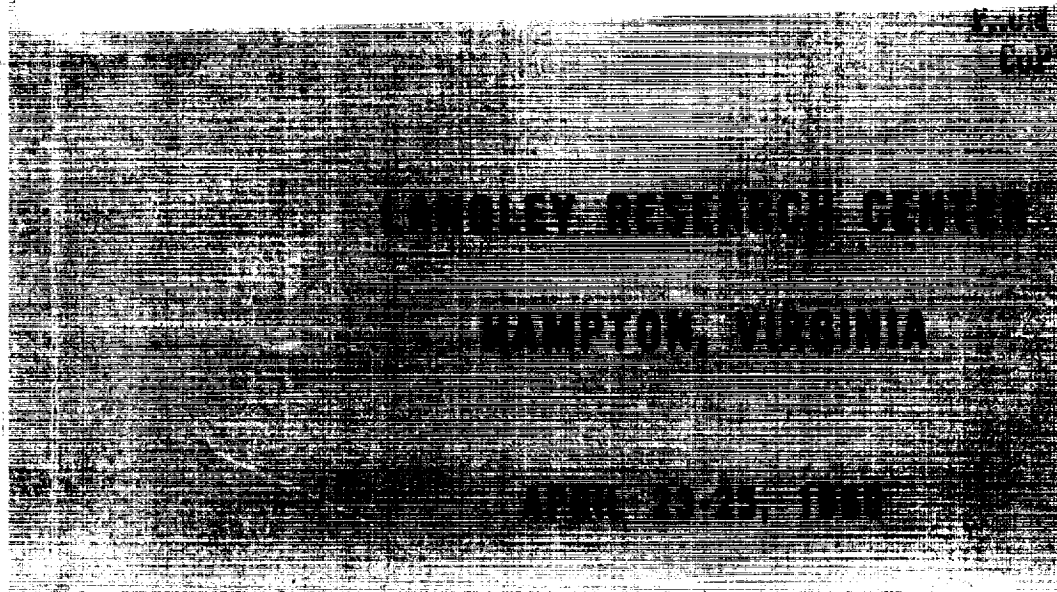
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LANGLEY RESEARCH CENTER

HAMPTON, VIRGINIA

APR 20-21, 1982

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S U M M A R Y

Langley representatives reviewed the Center's research on hypersonic propulsion with emphasis on materials aspects. They covered the Hypersonic Research Engine in detail. The Panel began a study that will be continued before, and at, the next meeting, designed to identify future materials requirements of hypersonic engines.

The Panel discussed Non-Destructive Testing (NDT) and Life Prediction methods for aircraft engines and arrived at a list of tentative research suggestions.

A Subpanel on superalloys submitted a list of research recommendations, which was modified by the Panel.

Future needs for facilities for engine materials research were discussed, and three were found that warrant more detailed study viz: (1) an engine facility for materials testing, (2) an NDT facility and (3) a facility for casting research.

NASA RESEARCH & TECHNOLOGY PANEL
ON
MATERIALS FOR AIRCRAFT ENGINES

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Langley Research Center

April 23-25, 1969

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MINUTES OF NINTH MEETING
OF THE
NASA RESEARCH AND TECHNOLOGY ADVISORY PANEL
ON
MATERIALS FOR AIRCRAFT ENGINES
NASA Langley Research Center
April 23-25, 1969

The ninth meeting of the NASA Research and Technology Advisory Panel on Materials for Aircraft Engines convened at 9:00 a.m. EST on April 23, 1969.

Present:

Dr. Robert I. Jaffee, Chairman	Mr. Albert E. Anglin, Jr.
Mr. Walter E. Binz, Jr.	Mr. G. Mervin Ault
Mr. Elihu F. Bradley	Mr. Michael B. Comberiate
Dr. Harris M. Burte	Mr. James J. Gangler
Mr. William R. Freeman, Jr.	Mr. Richard Pride
Mr. Dean Hanink	Mr. Richard H. Raring
Mr. Louis P. Jahnke	Secretary
Mr. John V. Long	
Mr. Ward Minkler	
Prof. Robert A. Rapp	
Mr. Winston H. Sharp	
Mr. John White	

Absent:

Dr. E. C. Burke
Mr. Philip Goodwin
Prof. Ray W. Guard
Mr. Francis B. Howard
Mr. Ira Petker

NASA Staff:

Mr. I. K. Loftin, Jr. Assistant
Director, Langley Research Center
Mr. Earl H. Andrews, Jr.
Mr. Tom F. Bonner, Jr.
Mr. L. Robert Jackson
Mr. Neale H. Kelly
Mr. Ernest A. Mackley
Mr. Eldon Mathauser
Mr. Mark R. Nickols
Mr. Bland A. Stein

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Visitors.

Mr. George Seely, WPAFB
Mr. Thomas Willis, WPAFB
Mr. Chester Furlong, AEDC
Mr. W. C. Beecraft, WPAFB
Mr. Irving Machlin, NASC

The Chairman stated that Mr. Francis Howard had resigned his FAA position in Washington to join the Navy's Office at Palm Beach; FAA has not yet named a replacement on the Panel. The Chairman introduced Mr. Irving Machlin who attended the meeting in place of Mr. Philip Goodwin.

SECRETARY'S REPORT

The Secretary reported that the NASA Research and Technology Advisory Committee on Basic Research, which is the senior advisory group to which the Panel and four other of NASA's research advisory bodies formally transmit recommendations for endorsement and coordination, had made three requests of its subgroups at its last meeting, April 16-17, 1969.

1. Since the Basic Research Committee meets but once a year, and always in late April or early May, it is obviously expeditious for the subgroups to schedule their last meeting of the fiscal year shortly before the Committee's annual meeting.

2. The Committee noted that an adequate review and discussion of the voluminous output of minutes and reports of its five subgroups is often difficult or impossible at its once-a-year meeting. Consequently, the Committee suggested that the subgroups periodically prepare position-papers, or concise versions of their recommendations and justifications, as an adjunct to their minutes and reports.

3. Noting that the identification of research facilities that will be needed in the future, especially those of high cost and long lead-times, is an important function of the subgroups and one that they have tended to slight, the Research Committee asked that increased attention be given to that matter.

INTRODUCTIONS

Mr. John Henry, Chief of Langley's Hypersonic Propulsion Branch, welcomed members of the Panel and of the Subcommittee on Airbreathing Propulsion, who were met in joint session to receive presentations by Langley representatives on propulsion systems for hypersonic flight and presentations by Air Force representatives on aeronautic technology and facilities of foreign countries.

Mr. Henry introduced Mr. L. K. Loftin, Jr., Assistant Director of the Langley Research Center, who briefly described the Center's research on aeronautics. At present, 33% of Langley's manpower is applied to aeronautics, compared with 24% three years ago. However, the absolute increase in aeronautical research is less than these numbers suggest because the Center's manpower ceiling is lower than it was two years ago. By July

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1969, total employees must be down to 3,849, compared with 4,300 two years ago. Mr. Loftin said that of the two chief constraints limiting aeronautical research--i.e., personnel ceiling and the total funds--the ceiling is the limiting one.

Langley's aeronautical research breaks down approximately as follows: supersonic 34%; hypersonic 24%; VSTOL 18%. There is arbitrariness in this breakdown because some work is applicable to more than one of the categories.

PRESENTATIONS ON HYPERSONIC PROPULSION

Mr. Earl Andrews of Langley's Hypersonic Propulsion Branch spoke on the environment and concepts of hypersonic airplanes. Copies of his unclassified slides are attached as Appendix I. He began with a discussion of the most promising kinds of power plants and fuels for speeds to Mach 24 and of the corresponding environmental factors, including altitudes, stagnation temperatures, dynamic and total pressure. (Figures 1-4)

Next, he described--with the aid of a full-scale mock-up--the Hypersonic Research Engine (HRE) designed and constructed, over the past three years, by AiResearch under a Langley Contract (Figures 5-9). These figures contain information on temperatures, heat fluxes, internal ducting of coolant, and materials, and illustrated the engine's basic configuration. Mr. Andrews pointed out that the cooling requirements will give rise to design and materials problems. He noted that to minimize the total cooled surface the designer must minimize the internal wetted surface. In order to further reduce cooling requirements he will probably want, or need, an insulating coating. Any such coating will have to be able to withstand a reasonable number of thermal cycles without spalling.

Mr. H. Neale Kelly, of Langley's Eight-foot High-Temperature Structures Tunnel Branch, described the structure, materials, and operation of the HRE in more detail. Prints of his slides are in Appendix II.

Mr. Kelly's talk covered, and the prints of his slides show data and other specifics on: the design and structure of the cooled panels; the design parameters of cooling fins; test results of brazed fins made from various materials; and results of creep test and fatigue tests of the materials used for the cooled panels.

In response to questions about the high cooling-equivalency ratio (H_2 needed to cool/ H_2 used as fuel), which in the HRE is approximately three, Mr. Kelly pointed out that the HRE designers did not make any special efforts to get a low ratio. Eventually, he believes, in real engines with well-defined range and economic goals, the ratio will be reduced by various design stratagems, such as coatings or lower wetted surfaces, to one or less.

Of the six most urgent needs of hypersonic engines, listed on Mr. Kelly's last slide (Figure 15, Appendix II), three dealt with materials (better high-temperature alloys; insulating coatings; and improved fabrication). In reply to questions about recently reported instances of incompatibility between some stainless steels and nickel-base alloys and gaseous hydrogen (GH_2), Mr. Kelly said that AiResearch was aware of these matters and had made tests that satisfied their engineers that there would be no trouble with the alloys in the HRE at the GH_2 pressures and temperatures encountered.

Mr. L. Robert Jackson, of the Aerothermal Elasticity Section discussed Langley's research on thermal protective systems (TPS) for liquid hydrogen (LH_2) tanks of hypersonic airplanes. Although LH_2 is by far the most efficient fuel on a weight basis, its low density aggravates tank-insulation problems, since a LH_2 tank is five times as big as a JP tank of equal RTU capacity, and because of the lower LH_2 temperature. Consequently, the tanks for hypersonic airplanes will require TPS of low weight and high efficiency. Also, the materials must be compatible with GH_2 and other environmental factors, at both high and low temperature. Its ΔT will be $2,000^\circ F$. - (cf. the $300^\circ F$ ΔT for the SST).

Mr. Jackson's first slide (copies of his slide are in Appendix III) illustrates the three major problems of LH_2 tank insulation: i.e. control of heat flow to fuel; cryopumping in the insulation space; and insurance of an inert space around the tank. He explained design concepts with vacuum insulation; multiwall foil structures and cryoevacuated foam insulation. His slides showed the facilities he used to evaluate experimental structures and results of tests of experimental tank. He described a design approach in which solid CO_2 is cryodeposited, then absorbs heat by sublimation during flight; this design led to the lowest weight. Mr. Jackson's summary slide listed the major problem areas and needs as: LH_2 test facilities; joining and sealing of very thin-gage alloys; methods of sealing polymeric materials; polymers with higher temperature capabilities; insulating material that prevents flow of LH_2 but yet permits outgassing, and facilities for systems testing of various TPS.

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Mr. Bland A. Stein, of Langley's Structural Materials Branch, reviewed the Center's materials research in support of hypersonic aircraft. Prints of his slides comprise Appendix IV. He began with a detailed description of the expected environment of a hypersonic cruise airplane in terms of temperature, time, and pressure at various locations on the surface and within the airframe. His slides listed the most promising materials for the several applications.

Mr. Stein next discussed the kinds of facilities that will be needed for the evaluation of materials and he showed diagrams and photographs of Langley's new Hypersonic Materials Environmental Test System, now about ready for full use (Figures 3-5 of Appendix IV).

Mr. Stein then discussed Langley's oxidation test of materials for non-refurbishable heat shields, including microprobe analysis of composition changes immediately below the surface. Results are shown in Figures 6-9. He concluded with an account of the manufacture and evaluation of Al-Sn-Mo-coated tantalum alloys, tested in the Center's radiant heating facility (Figures 7-10).

Mr. Ault, at the Chairman's invitation, listed the Lewis research tasks that have relevance to, although not necessarily motivated solely by, hypersonic aircraft. He noted that certain of these research tasks have been reviewed and discussed at previous meetings of APMAE. They are: LH₂ tank materials research; LCF at LH₂ temperature; insulation materials for cryogenic tanks; insulative oxides coatings for cooled metals (rocket nozzles); research on superalloys for use above 1600°F; research on powder metallurgy approaches to TD-type alloys; fiber strengthening of superalloys; refractory metals and protective coatings for superalloys; and fatigue prediction theory and experiment.

On the second day, the Panel met apart from the Propulsion Subcommittee. The first business was a supplemental presentation on the HRE by Mr. Tom Bonner, assisted by Messrs. Ernest Mackley and Neale Kelly. This talk put greater emphasis on the materials aspects of the HRE and was intended also to afford Panel members more opportunity for questions and discussion.

Mr. Tom Bonner began with a review of the overall objectives of the HRE project (listed in Figure 1 of Appendix V). He went on to discuss: the timing of the various phases of the project; details of the original test plan with X-15 as a test bed; and concluded with more detail on manufacturing processes (Figures 2-4).

The project was begun in 1964. Its objective was the design and construction of an 800 pound max-weight engine that could be tested to Mach 7 while hanging under the aft end of X-15. With the termination of the X-15 flight program, the HRE lost its chance of a flight test, but both Langley and Lewis have ground facilities that can make several kinds of tests to Mach 7.

The HRE's designers limited the temperature of loaded structures to 1600R, non-loaded ones to 2060R. Probably the most severe gaseous hydrogen (GH_2) situation that any of the structural materials will experience will be 280 psi - 1300R at the plenum, just prior to injection to the burner location. Mr. Bonner said that AiResearch had tested all the materials that will be in contact with GH_2 at the actual operating conditions.

Mr. Kelly pointed out that the HRE is strictly a research device, designed to test new concepts, such as hypersonic combustion and LH_2 panel cooling. No special efforts were made to get high efficiency or thrust. He added that eventually, when hypersonic airplanes are designed for practical flight, the engines would be quite different. They will have to be able to run continuously for about one hour, since that would be about the maximum flight time between any to earth-locations, and would have to be good for many flights. He said that now-available alloys and fabrication methods will do for the HRE, but practical and useful engines will call for new, improved, and optimized materials, and especially new and better methods of fabrication.

DISCUSSION OF HRE MATERIALS

Prof. Rapp asked if there was any concern about atomic hydrogen dissolving in, and diffusing through, the nickel-alloy cooling panels, and then combining with the metal oxide on the cold side. Should this occur, the steam which would immediately form could blow off any protective oxide film and thus lead to rapid loss of metal by oxidation. Mr. Kelly said that in the limited test runs to date, this sequence of events has not been observed.

Mr. Hanink suggested that TD nickel might be a very good material for heat exchangers of hydrogen-cooled parts because its favorable combination of ductility, thermal expansion (which indicate good LCF) compatability with GH_2 , and high-thermal conductivity.

Dr. Jaffee suggested that a molybdenum heat-exchanger, coated on the oxidizing side, might be good in view of its high thermal conductivity.

Mr. White saw the materials problems of hypersonic engines as springing from (1) the high heat flux. of $800 \text{ BTU/ft}^2/\text{sec}$. (2) low-cycle fatigue, (3) hydrogen compatability and (4) the cooling-efficiency ratio matter. Mr. Hanink said that the heat flux would not be very much higher than that in some parts of today's jet engines.

Dr. Jaffee suggested that a precracked coating (as a thermal barrier) might be worth examining because of its better spalling resistance. Mr. Freeman remarked that there is always a danger that coating cracks may run into the substrate.

Mr. Bradley suggested that cobalt base alloys (e.g. 133) are worthy of consideration, in view of their melting point (higher than Ni), good oxidation resistance, high strength, and low thermal expansion. He was not aware of any data on their GH_2 compatability. Dr. Burt added that TD cobalt should be considered.

The Chairman asked if Panel members believed that a Subpanel on Hypersonic Engine Materials should be appointed. The consensus was negative because it appeared that at present the materials requirements could not be defined well enough to establish requirements and research goals.

Mr. Hanink thought that if the communications between designers of advanced engines, such as the HRE on the one hand, and materials researchers on the other, could be improved, it might be possible to define materials needs sufficiently well to justify materials research now. He recalled that he had made this same observation at previous meetings, in connection with advanced jet engines. He suggested that the Panel agree on, and submit to the Propulsion Subcommittee, a formal procedure

to follow to improve communications between designer and materials engineers. The first step of the procedure is submission of questionnaire-like outline, addressed to the designer, as follows:

Design Interaction

Information required.

1. Application characterization of mission and its effects on
 - a. Cycle time
 - b. Stress mode
 - c. Temperature
 - d. Other environmental factors
2. Design criticalities/limitations and relationships
 - a. Performance goals
 - b. Materials/structurers availability
 - c. Durability-endurance goals
3. Time Schedule of Needs

The materials people would respond to the above in accordance with the following forms.

Materials Response

1. Materials Engineering Data
 - a. Statistically expressed
 - b. Scope of, and relationship to, application
 - c. Timeliness
 - d. Format
2. Design Allowables
3. Quality Assurance
4. Fabrication Restraints
5. Availability
 - a. When
 - b. Quantity
6. Costs
 - a. Now
 - b. Future

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As an additional RAPMAE effort to focus on problems of hyper-sonic engines, the Chairman asked Mr. Pride to consult further with Langley and AiResearch engineers who are connected with the HRE and try to identify and evaluate the likely materials barriers -- e.g. GPa compatability, LCF, joining, fabrication, emissivity, coatings, creep, hydrogen diffusion, etc. Mr. Pride agreed to do so and to send his findings to the Panel members in time for planning of discussion of the subject at the next meeting.

Report of NDT Subpanel

Dr. Burte, Chairman of the Subpanel on NDT and Life Prediction Methods, stated that the subpanel met at WPAFB on March 25 and 26 and drafted a report, which he distributed (Appendix VI). Dr. Burte observed that during the past ten years or so, materials engineers and physicists had extensively explored very many phenomena for possible applicability to NDT. As a result, there are now several new and very promising methods of NDT that deserve more development. Dr. Burte recommended more research to establish correlation between NDT indications and service experience, in preference to more fundamental research on new NDT approaches, and also more work on pattern recognition.

During discussion of the Report, the Panel suggested that the following "areas" be added to the list beginning at the top of Page 2 of Appendix VI: defects in single crystals; composite structures; residual stress; and overtemperature damage.

The Panel discussed the need of a national center for NDT; consensus was negative on recommending such an establishment at the present time.

Dr. Burte distributed a short discussion on fatigue life prediction for jet engines (Appendix VII), and expanded on it with a description of how statistically-based reliability theory was applied to the wing box of the Air Force's fleet of K-135 tankers. A Technical Note on this study is processed; Dr. Burte will have copies sent to Panel members.

Mr. Ault suggested that, for clarity, Low Cycle Fatigue be identified as to whether it is "thermal" (LCTF) or "mechanical" (LCF). The chief distinction is that in LCTF, the stresses are thermally induced, and occur over a range of temperatures, so that mechanical properties are changing. LCF implies mechanically induced stress at constant temperature. In both cases, special

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problems arise when temperature exceeds 0.4 to 0.5 of the melting point, where creep becomes important. LCTF occurs at temperatures above 0.4 of the alloys melting point. The Panel concurred with this suggestion.

Mr. White observed that LCF is much easier to deal with than LCTF, and that most of the research, is and should be, on LCTF.

Dr. Burte concluded with recommendations that:

1. A survey be made to ascertain the amount of current R&D on LCF and life prediction.
2. If the survey shows a level-of-effort of less than 10 to 12 tasks, it should be increased to approximately that level.
3. LCF theories should be tested by controlled experiments with real engines operating under representative service conditions.
4. Consideration be given to the application of the reliability approach used on airframes to engine parts.

Report of Superalloys Subpanel

Mr. Sharp passed out a list of seven recommendations of the Subpanel on Superalloys for discussion. Comments on the indicated recommendation-numbers follow:

No. 1 Emphasis should be placed on use of powder Metallurgy processes for use with hard-to-forge alloys and for control of grain size. Forging alloys should be added to this recommendation.

No. 2 The temperature range should be 900°- 1400°F. Better ultimate strength, creep strength, and grain size control should be added to the listed research goals.

No. 3 The title should be, "Hot Corrosion and Oxidation."

No. 4 Mr. Bradley pointed out that one of the major advantages of the directional solidification method is that it frees alloy developers of restrictions and restraints imposed by requirements for good grain-boundary properties. The requirements often necessitate

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compromises and trade-offs to get satisfactory grain bulk characteristics. He reported that P&W have made and tested more than 20,000 directional solidified engine parts. Techniques for making long-grain parts are good enough now for application, but single-grain parts need more development. The chief problem of directional solidification is its 100% to 200% higher cost.

No. 5 Expand recommendation to cover all fibers, not just metal fibers.

No. 7 Add "casting variables" to the list of examples of needed knowledge.

The recommendations, as revised by the full Panel, are attached as Appendix VIII.

Report of Subpanel on Composites

Mr. Long stated that the Subpanel had no reports or recommendations in final form to add to their report appended to the minutes of the last meeting. Their recommendations, however, are under review and may be modified before the next meeting. He stated that the major broad problem-areas of composites are (1) Process Techniques, (2) Test Methods, and (3) Costs.

Discuss Needed Facilities for Engine Materials Research

In response to the NASA Research Advisory Committee's request that the various Subcommittees examine NASA's needs for test facilities in their respective areas of responsibility, especially those facilities that require substantial time for design and construction, the Chairman asked the Panel to begin an inquiry into the needs for new facilities for research on engine materials. He noted that on several occasions in the past, the Panel had discussed NASA's need for a real engine to test new materials, but had always concluded that such tests can be done better and cheaper by engine manufacturers.

Mr. Ault stated that the Lewis Center has a J-75 jet engine that is specially designed and instrumented for research in cooling technology. This facility is not well suited for materials research and not so used.

Mr. Jahnke pointed out that NASA has access to the J-93 engine, with spare parts, left over from the B-70 project. He suggested that the Panel consider how they could be used for materials testing. The consensus was that a test facility built around them would be too costly and inflexible.

Mr. Ault said that Lewis is seriously considering the construction of a new test facility with a real engine, that could be used for materials research on all engine components e.g. fan, compressor, turbine, gas generators, etc.

Mr. Hanink suggested strongly that before Lewis makes final decision on such a facility, they consult all engine manufacturers and give them an opportunity to recommend desirable characteristics and uses.

Mr. Freeman noted that first costs and operating costs would be lower if the engine in such a facility were a small one.

The Panel agreed that NASA's need for an engine test-facility with materials test capabilities deserved further study. Messrs. Hanink, Bradley, and Jahnke agreed to examine the matters in greater detail and send their opinions on approximate specifications to the Secretary for transmittal to the Panel and for review at the next meeting.

The Chairman asked for suggestions for other new facilities needed for research on engine materials. The Panel agreed that a special NDT facility and a Casting Laboratory were worth study.

Mr. Binz agreed to prepare a specification and justification for a NDT facility, and Mr. Hanink for a casting laboratory. Results of their studies will be sent to the Secretary in time to forward them to the full Panel for discussion at the next meeting.

Members Reports

Dr. Burte distributed copies of current resumes (Forms 1122) of 83 Air Force tasks closely related to materials of interest to aircraft engines.

Mr. Pride handed out copies of brief status reports of seven research tasks at Langley of special interest to the Panel.

Mr. Machlin distributed copies of status reports of 11 Navy research tasks on high temperature materials for structures of propulsion systems.

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Mr. Bradley reported a recently discovered embrittlement phenomenon in superalloys. Troubles with low ductility in creep tests were found to be due to trace amounts of bismuth, probably introduced in tantalum scrap. Three parts per million (3ppm) causes serious embrittlement; Mr. Bieber of INCO has data that suggests that 1ppm may be enough. The bismuth embrittles by a mechanism involving segregation at grain boundaries. Mr. Jahnke noted that silver can act in a somewhat similar way. Failures of Rene' 80 have been attributed to 800ppm of silver. Other data suggest that 5-10ppm was harmless. The tolerance level is uncertain.

Next Meeting

The Panel scheduled its next meeting for September 24 and 25, at the WPAFB, Ohio. The major topic will be NDT and Life Prediction.

The formal business meeting adjourned at 12 Noon on April 25, 1969. On the afternoon of April 25, Langley representatives conducted Panel members who elected to inspect materials research facilities, on a tour of the Fatigue Laboratory, the 3-foot High-Temperature Structures Tunnel, and the Hypersonic Materials Evaluation Test Laboratory.

Richard H. Ramsey

APPENDIX I

E. H. ANDREWS

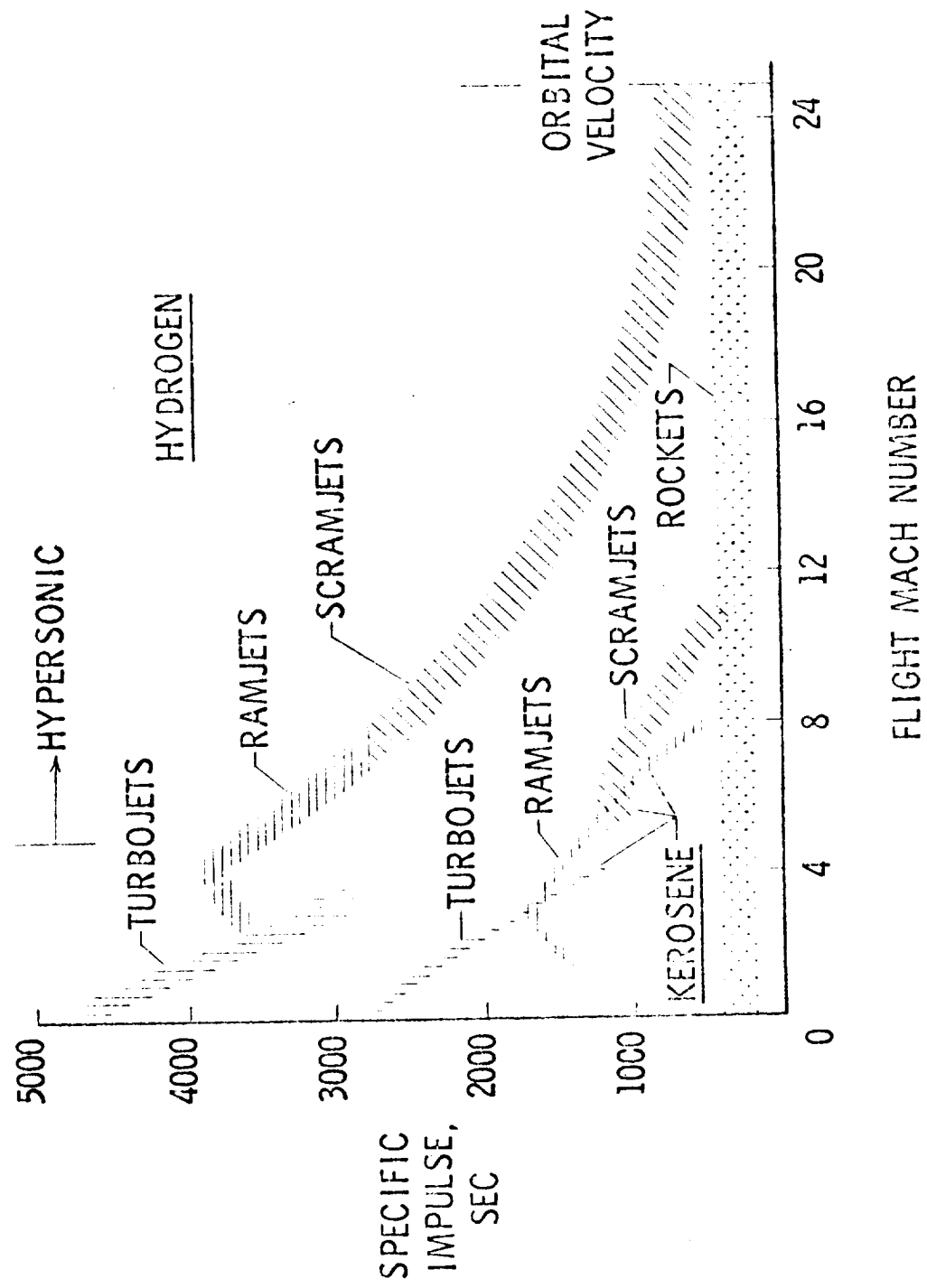
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E. H. Andrews

Figure List

- SLIDE 1. Specific Impulse for Air-Breathing Engines and Rockets
2. Hypersonic Cruise Vehicle
 3. Airbreathing Propulsion Operating Regime
 4. Hypersonic Cruise Environmental Conditions
 5. Stagnation Conditions for $q = 1500$ psf
 6. HRE Design Features
 7. HRE Design Conditions
- [Figure is confidential (title unclassified)]
8. Spike Tip Cooling
 9. Cowl Leading Edge Concepts
 10. Strut Cooling
 11. (a) Moving Parts Sealing
 - (b) Regen Panel Inserts
 12. Hypersonic Propulsion System Concept

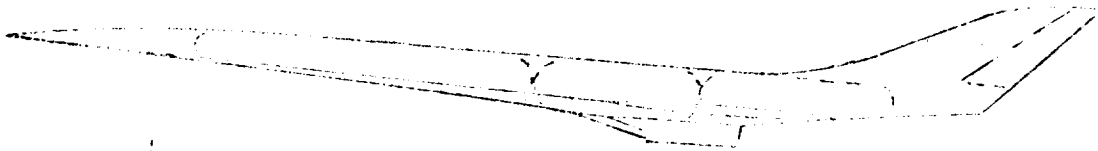
SPECIFIC IMPULSE FOR AIR-BREATHING ENGINES AND ROCKETS



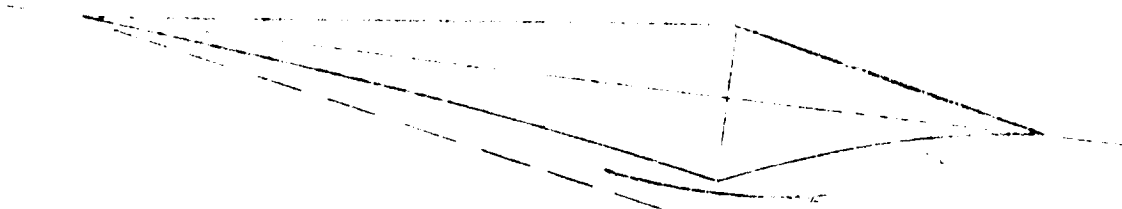
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HYPersonic CRUISE VEHICLE



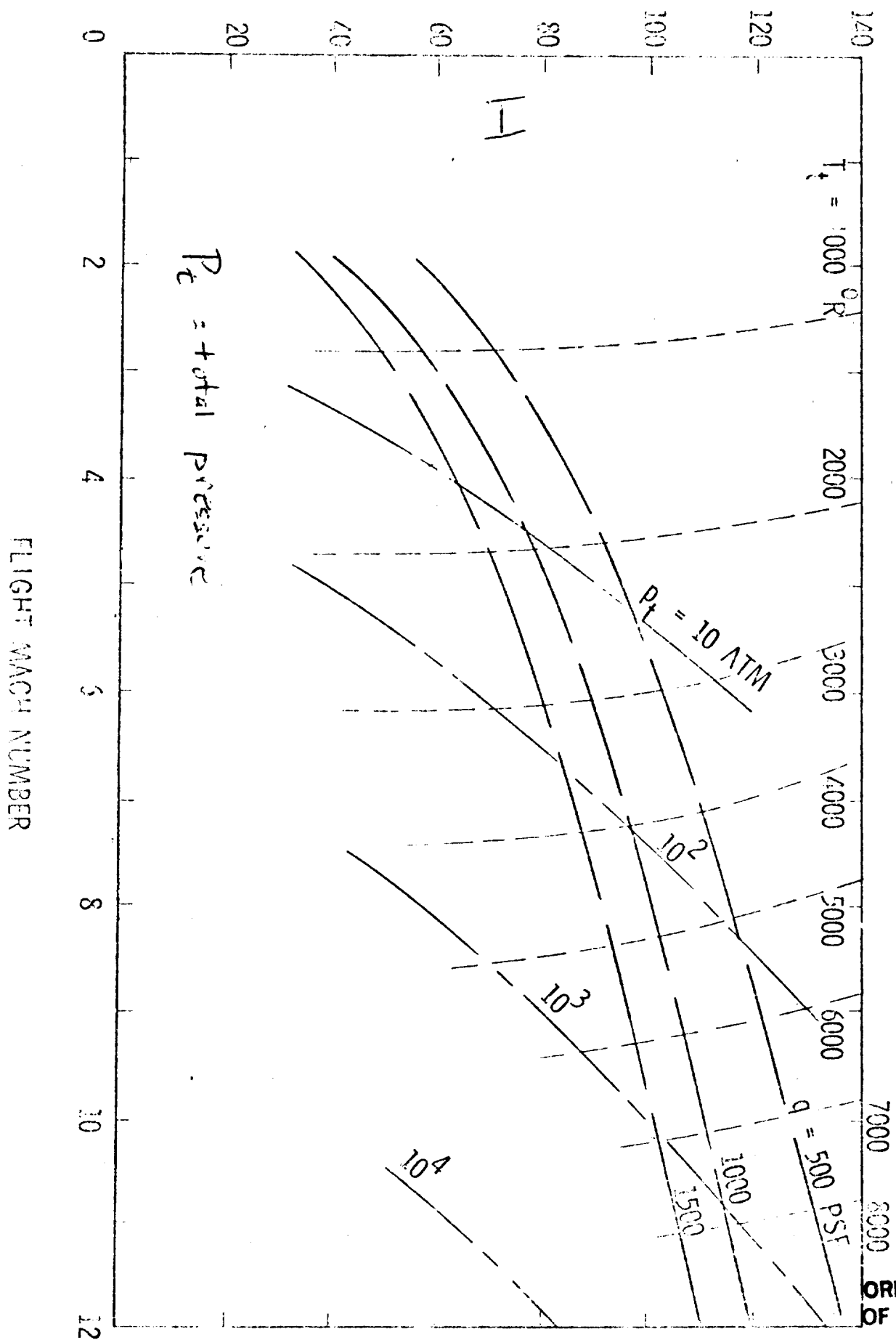
CONFIGURATION



FLOW MODEL

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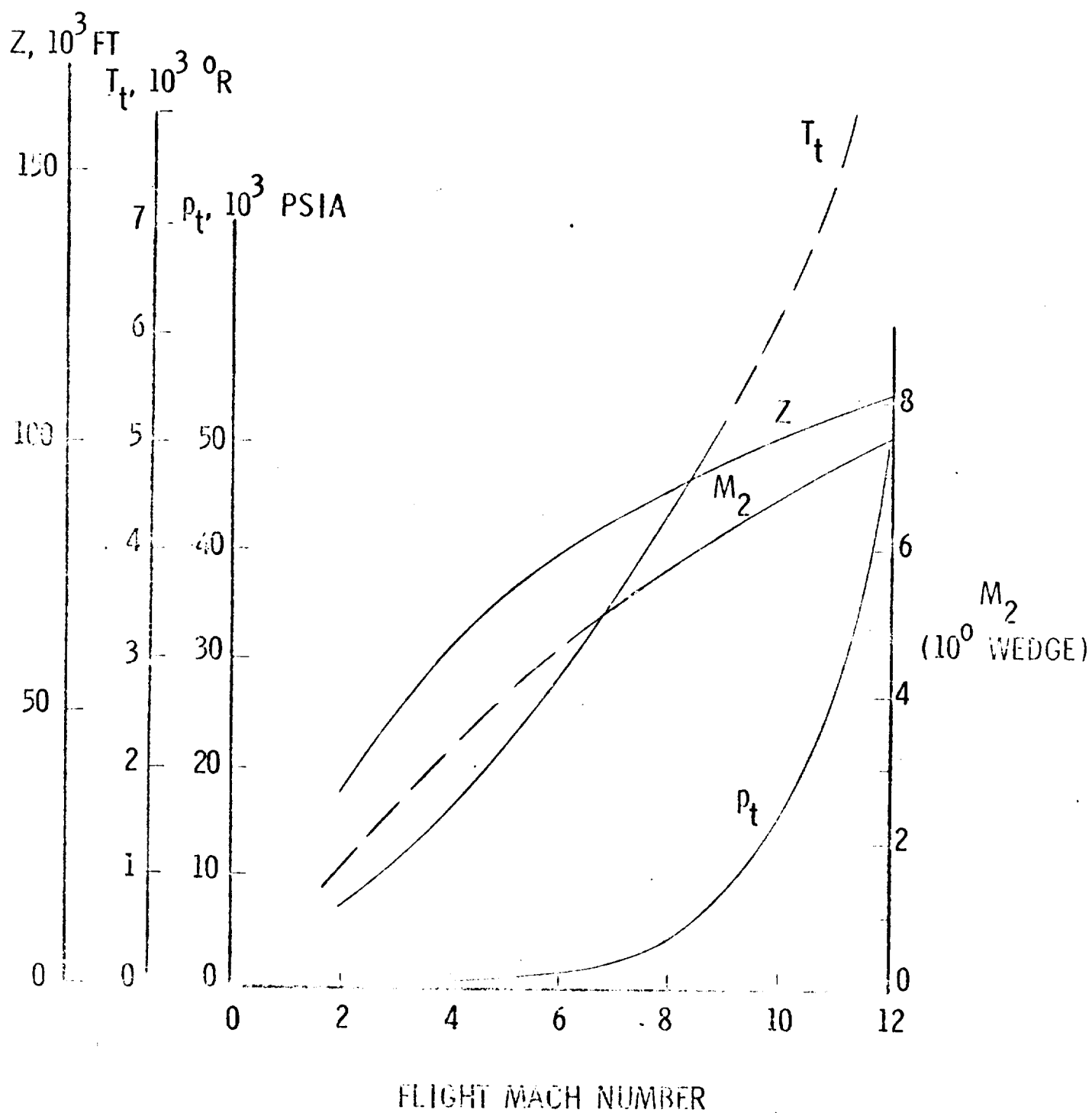
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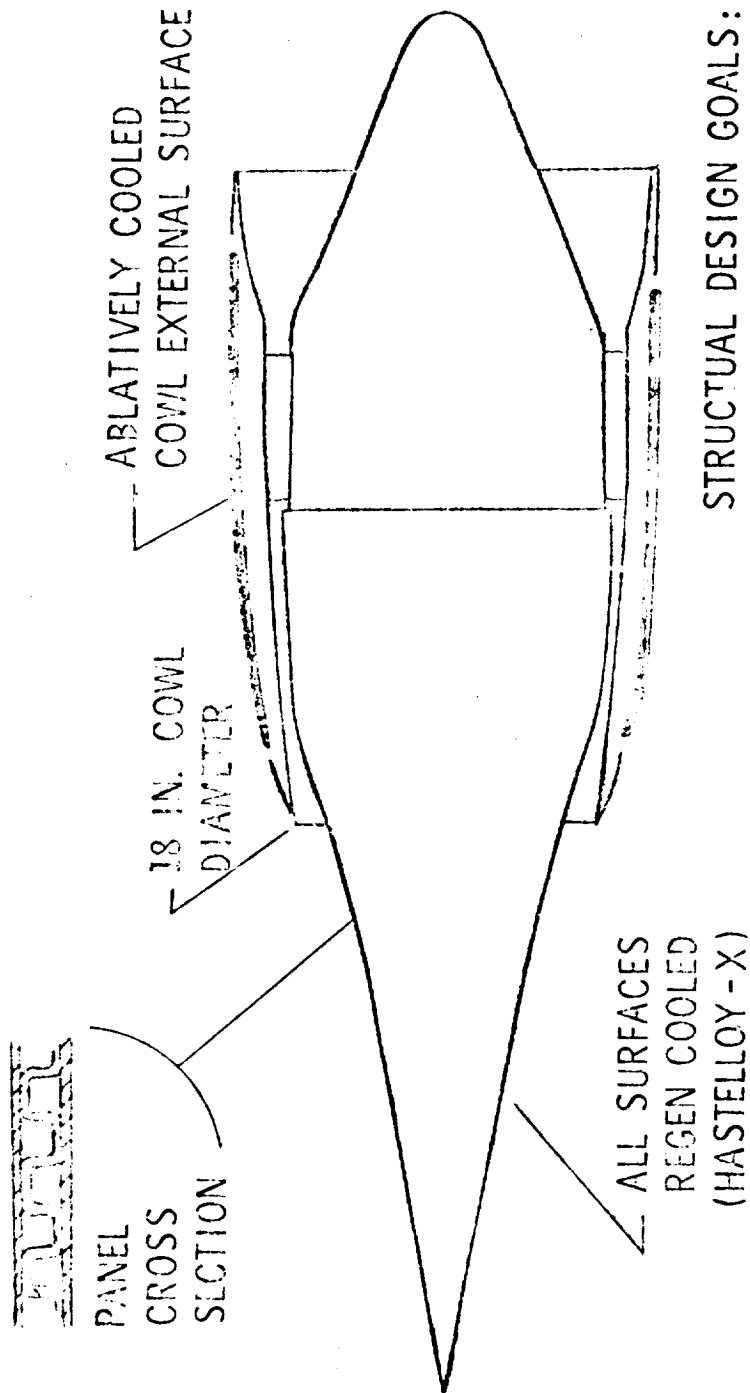
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STAGNATION CONDITIONS FOR $q = 1500$ PSF



HRE DESIGN FEATURES

90 INCH LENGTH

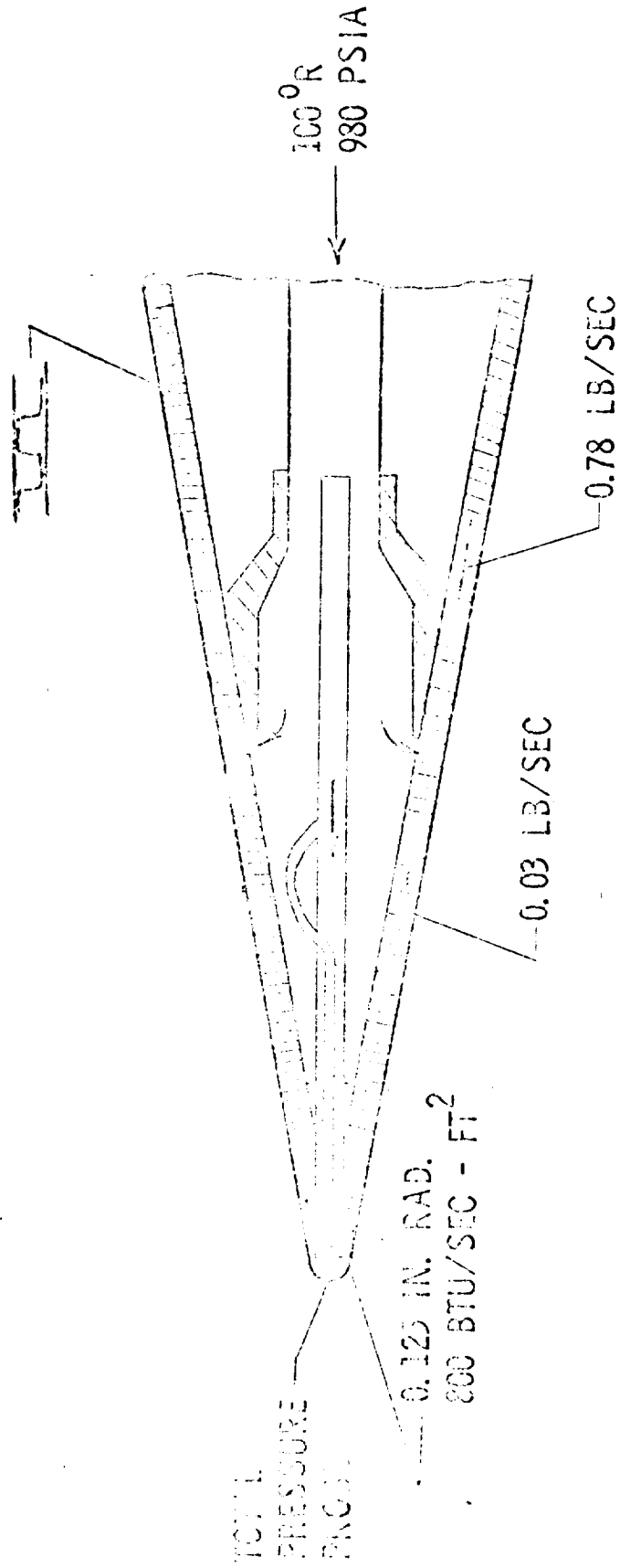


STRUCTURAL DESIGN GOALS:

- HOT WALL < 2060 °R
- COLD WALL < 1600 °R
- ΔT < 1200 °R
- 100 CYCLE LIFE

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SPIKE TIP COOLING

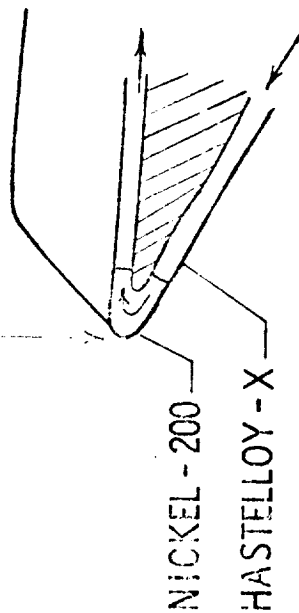


HASTELLOY-X { OUTER SKIN
REGEN PANEL FINS

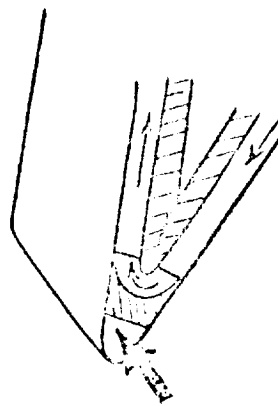
COWL LEADING EDGE CONCEPTS

18 INCH COWL DIAMETER

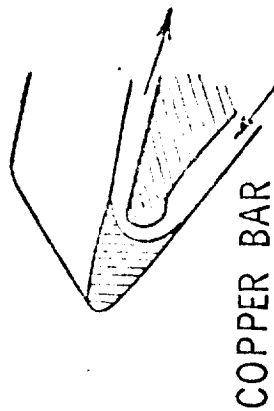
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1700 BTU/SEC - FT²



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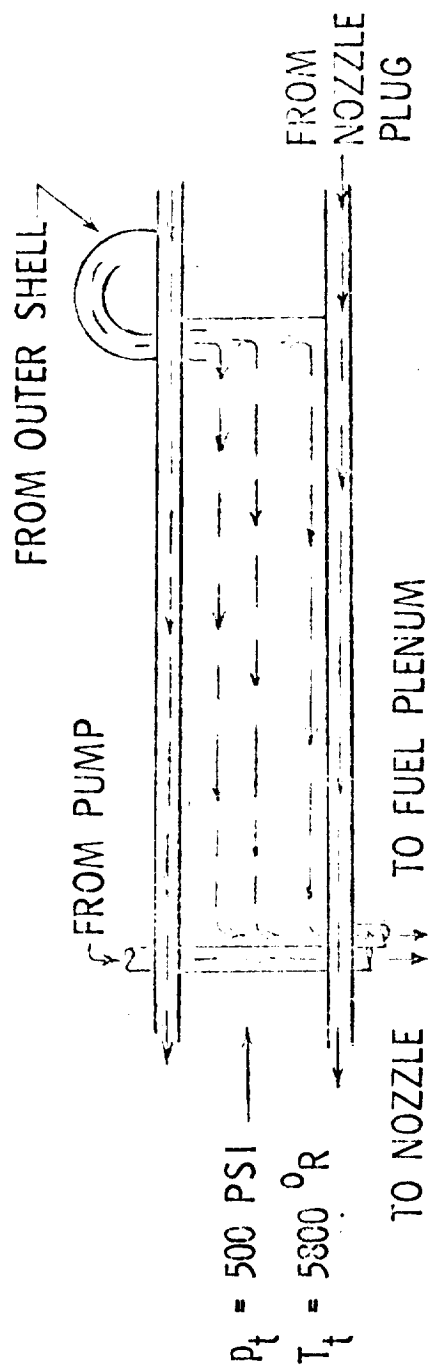


PARALLEL FLOW

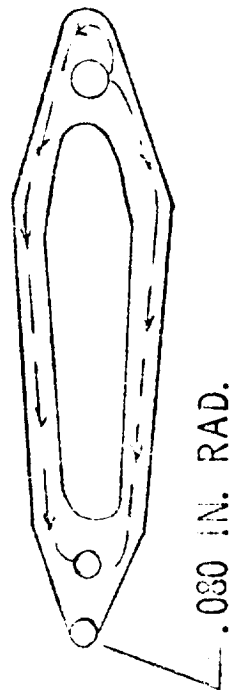


H

STRUT COOLING

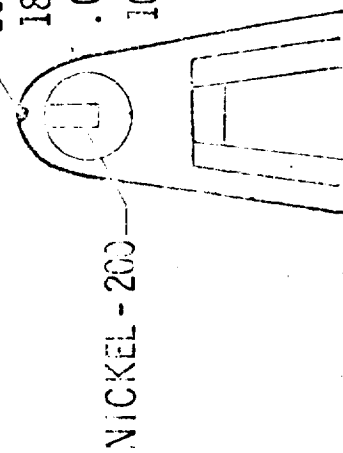


1600°R
 $1870 \text{ BTU/SEC} - \text{FT}^2$
 $.057 \text{ LB/SEC}$
 100°R



I

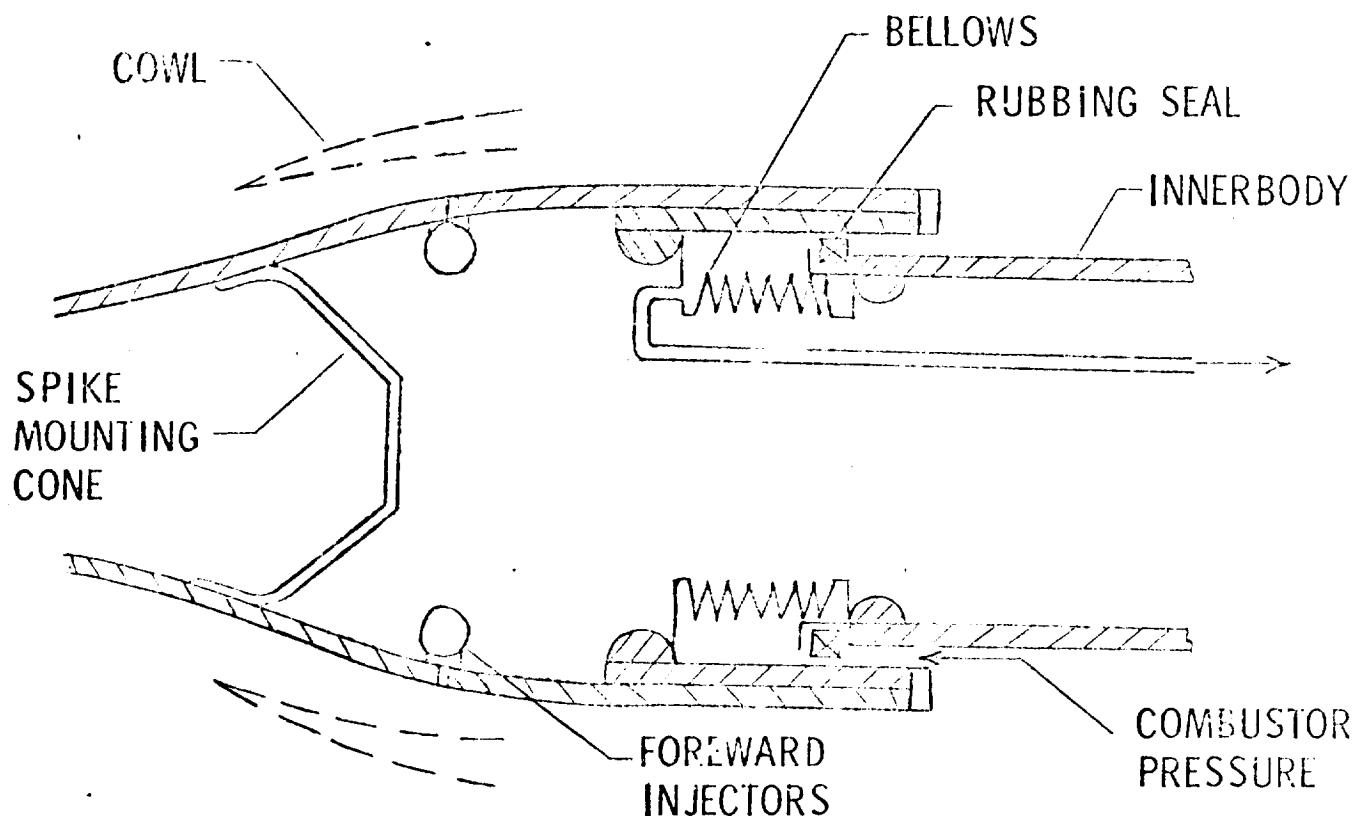
HASTELLOY - X



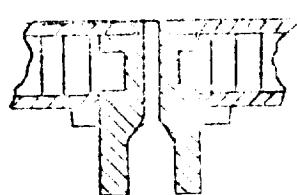
MOVING PARTS SEALING

I

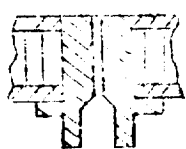
24



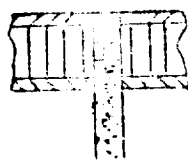
REGEN PANEL INSERTS



STATIC TAPS



THERMOCOUPLE



FUEL INJECTOR

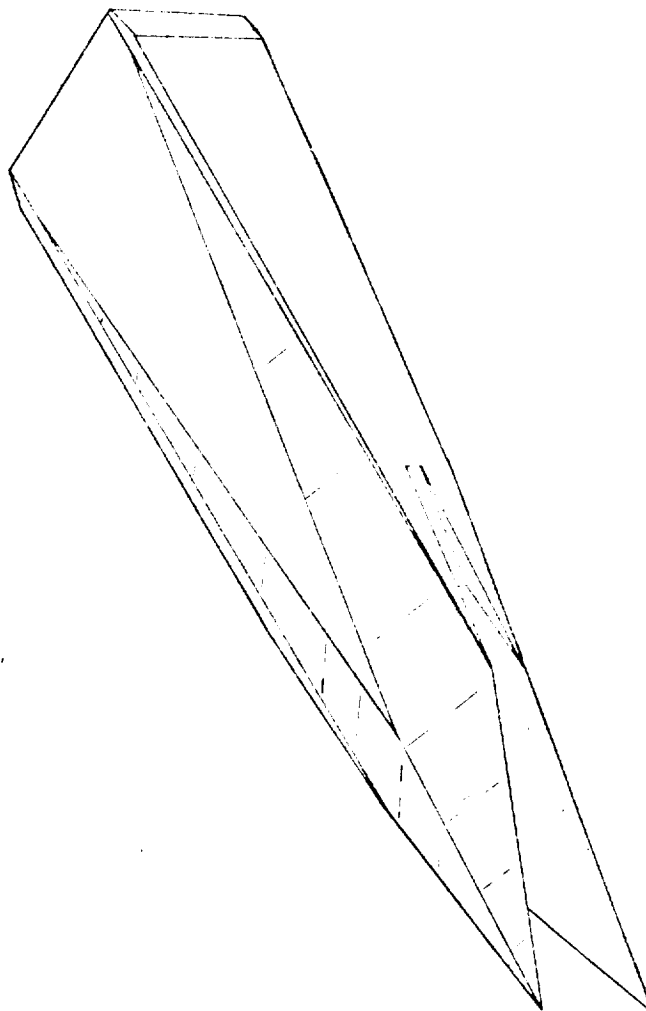


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I

HYPersonic PROPULSION SYSTEM CONCEPT

FIXED GEOMETRY

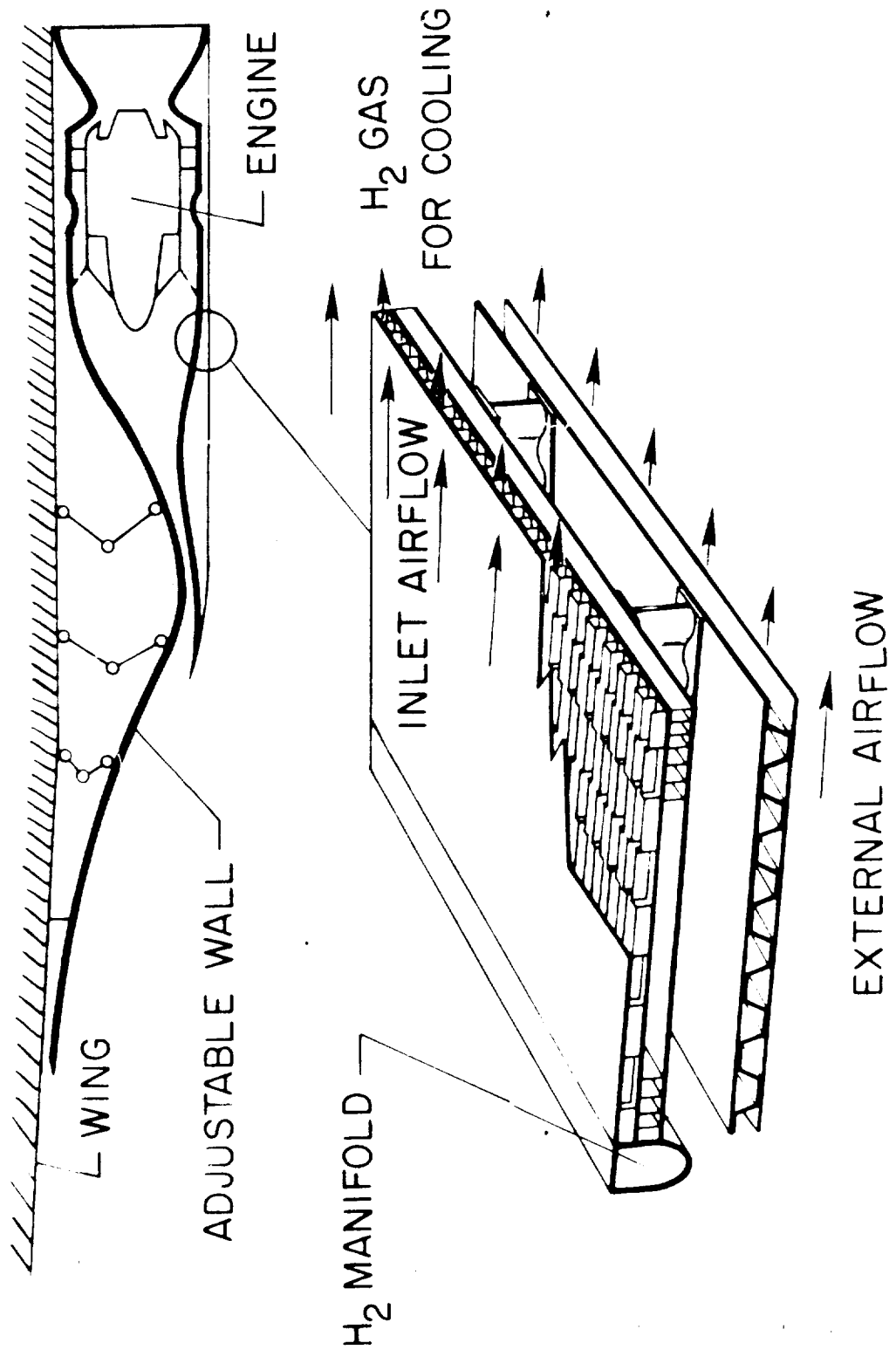


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APPENDIX II
NEALE KELLY

26

PROPULSION SYSTEM STRUCTURE
TWO-DIMENSIONAL AIR INLET



FIN SELECTION

$l = 2 \text{ FT.}$; $Q/A = 250 \text{ BTU/SEC-FT}^2$; $(T_{H2}) \text{ OUTLET} = 1110^\circ\text{F}$

$t_f = 0.003 \text{ IN.}$

MAXIMUM FIN
TEMPERATURE,
 1540°F

MAXIMUM FIN
DENSITY,
40 FINS/IN

$h_f, \text{ IN}$

FIN WEIGHT,
 LB/FT^2

0.100

0.075

0.050

0.025

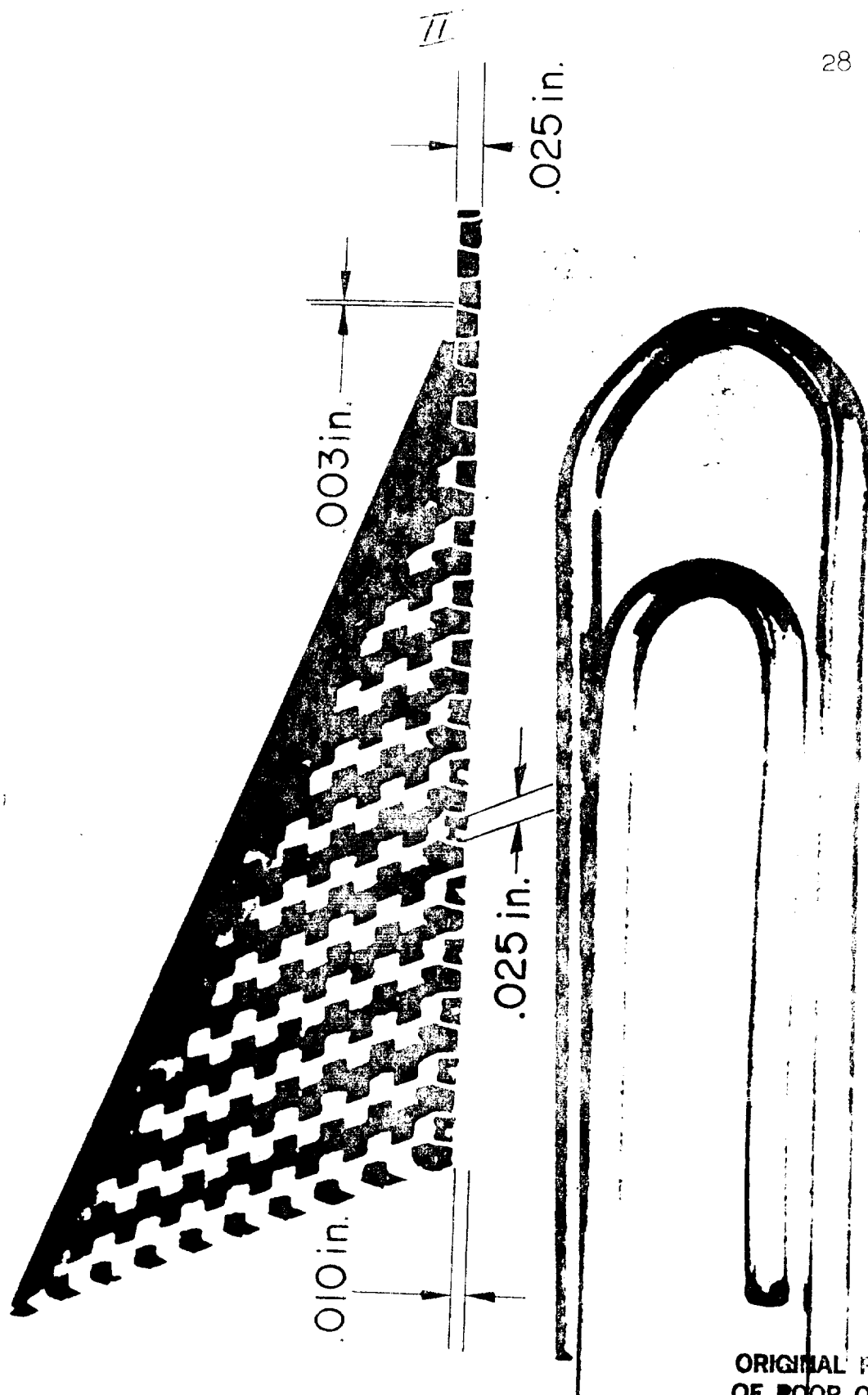
BULL
STRENGTH

MINIMUM HEIGHT

FINS/IN.

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TYPICAL HYDROGEN HEAT EXCHANGER

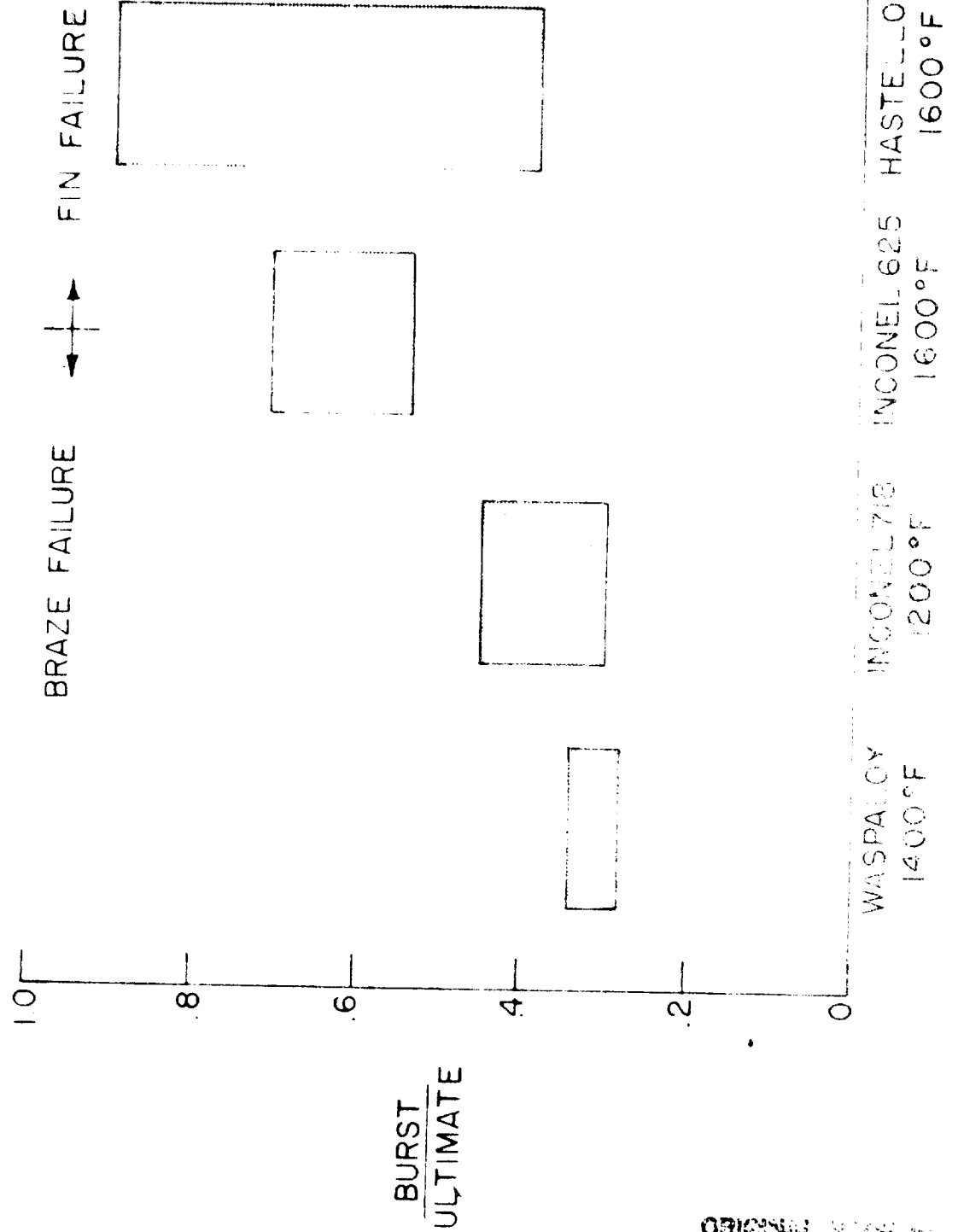


HU-8T TEST SPECIMEN



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BURST STRENGTH RATIOS

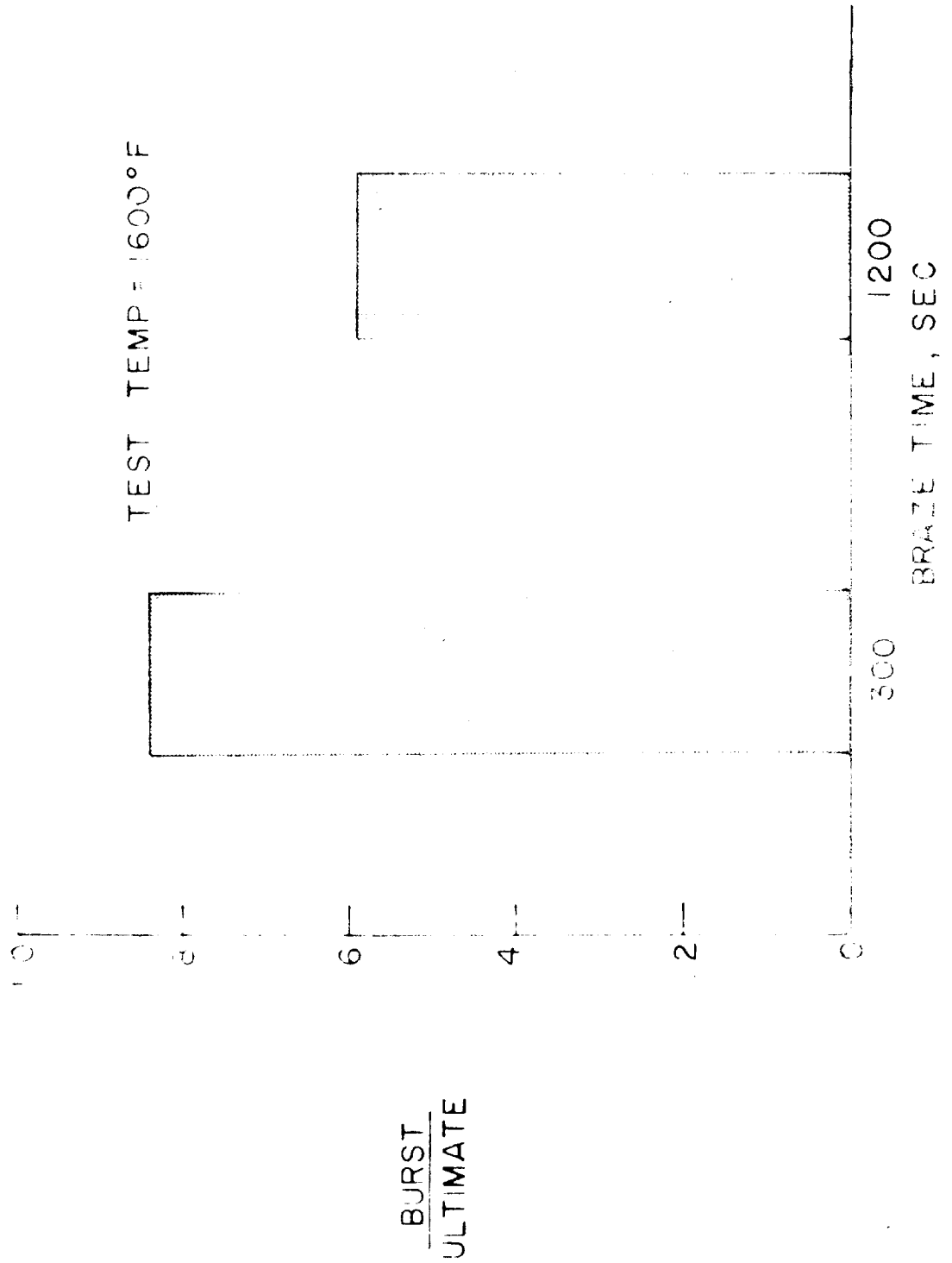


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BRAZING TIME EFFECT

HASTELLOY X - PALNIRO 4 (30AU-34PD-36NI)

TEST TEMP = 1600°F

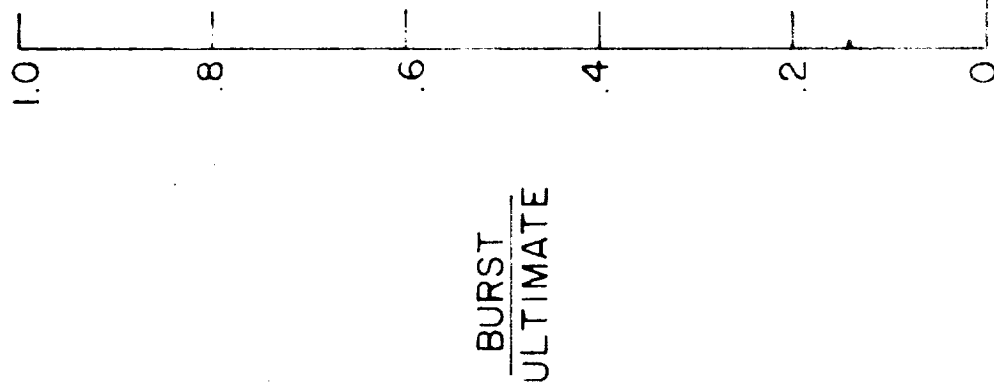


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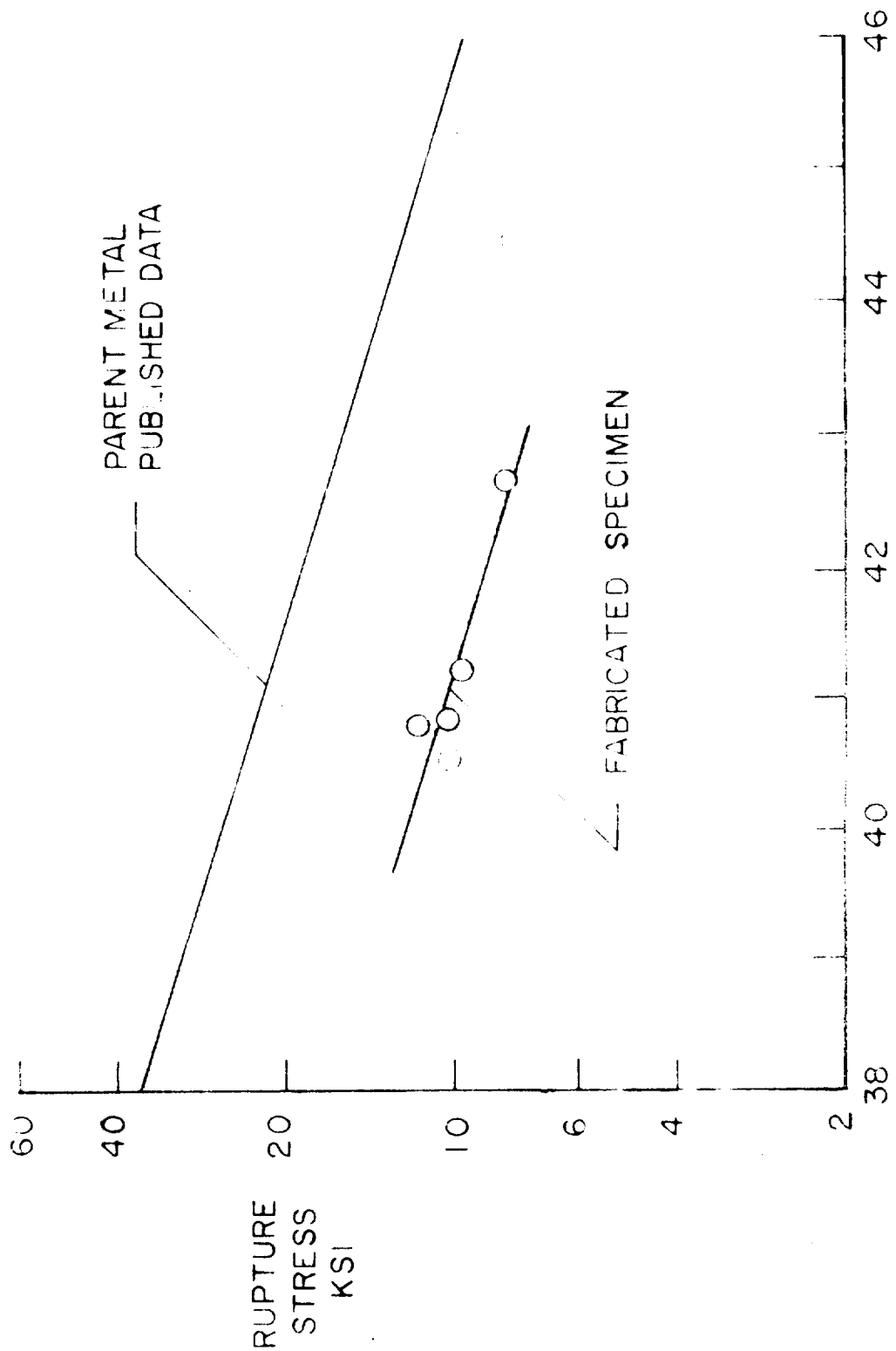
FIN GEOMETRY EFFECTS

HASTELLOY X - PALNIRO 4(30AU - 34PD - 36NI)

TEST TEMP = 1600°F



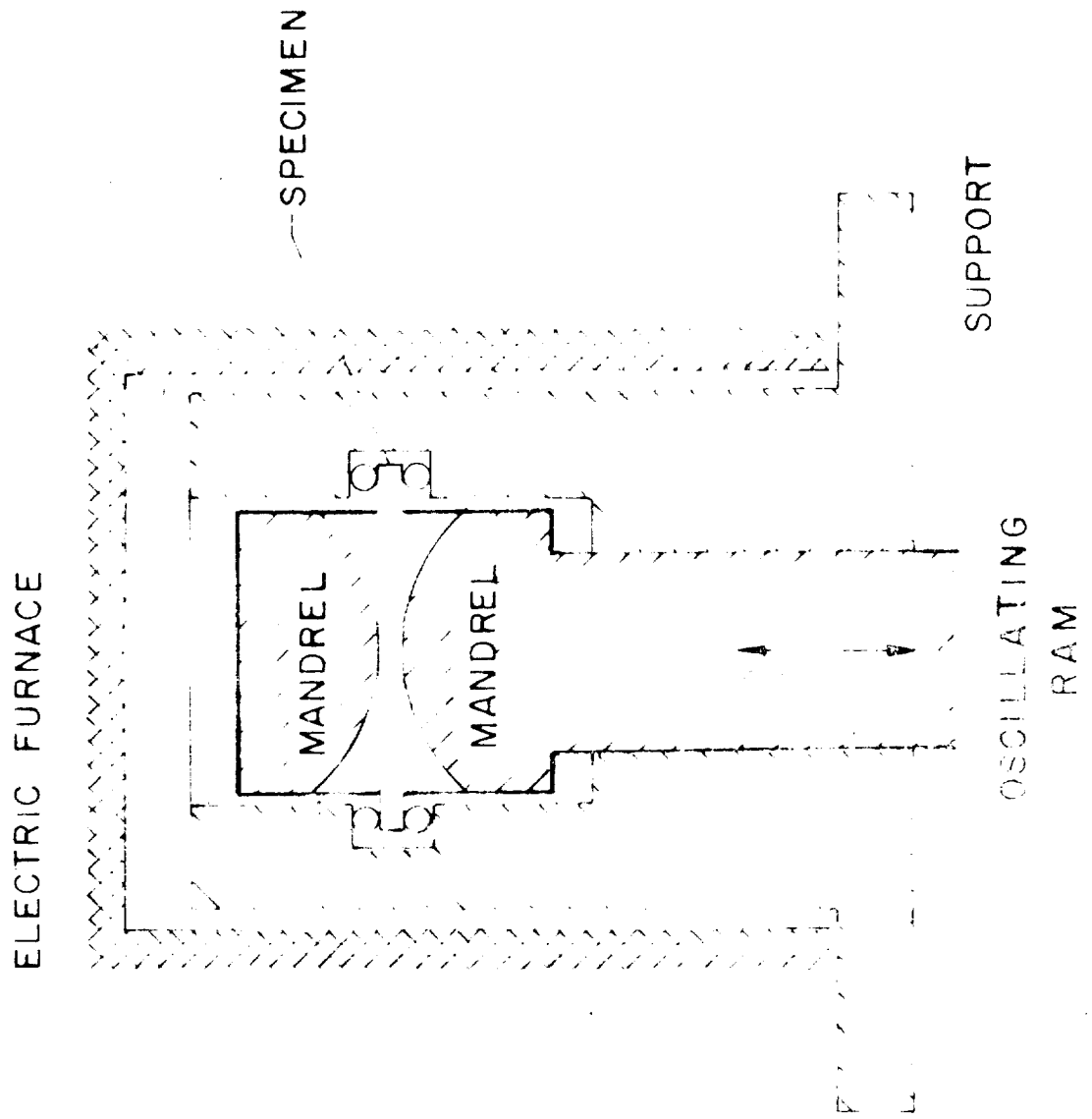
CREEP RUPTURE HASTELLOY X



LARSON MILLER PARAMETER

$T, ^\circ R \quad 20 + \text{LOG } t, \text{ HRS } 10^{-3}$

LOW CYCLE FATIGUE TEST APPARATUS



LOW CYCLE FATIGUE

INCONEL 625 - 1540°F

○ PARENT METAL
□ FABRICATED SPECIMEN

THEORY
PARENT METAL

EXPERIMENT
PARENT METAL

0.1

0.2

2

LA-100
1962

STRESS
S/N

.06

.04

.02

0.1

.0061

ESTIMATED

241

10

33

1 2

4 6

10 20

40 60

100 200

400 600

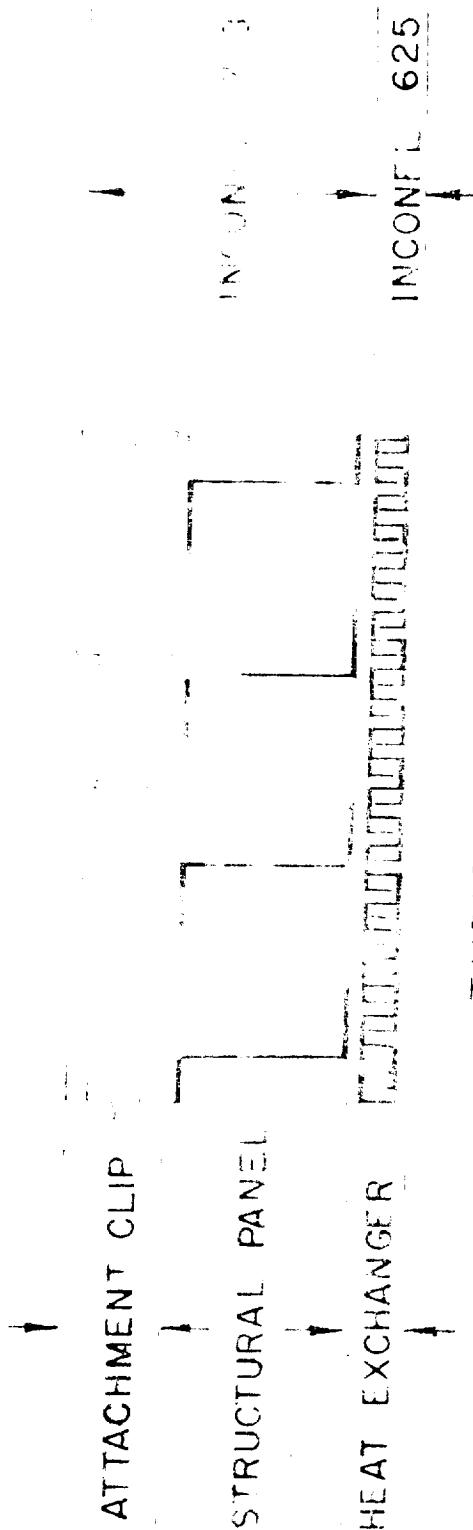
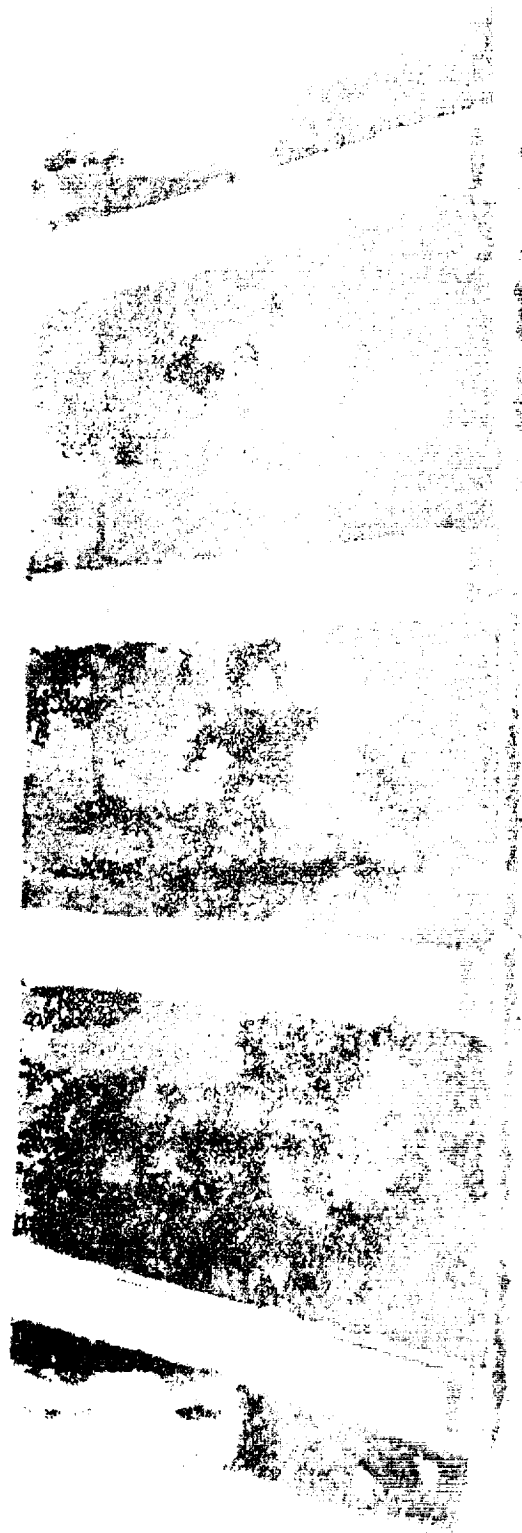
1000

N, FATIGUE LIFE, CYCLES

ORIGINAL FIGURES
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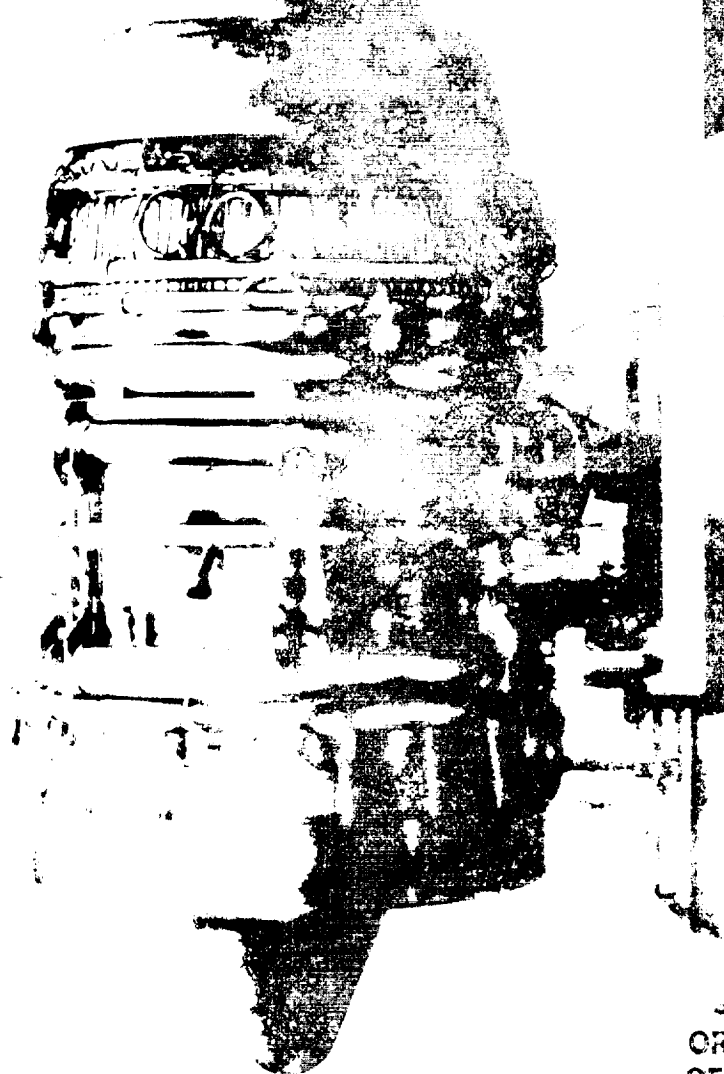
72

14 BY 20-- INCH COOLED PANEL



TYPICAL SECTION

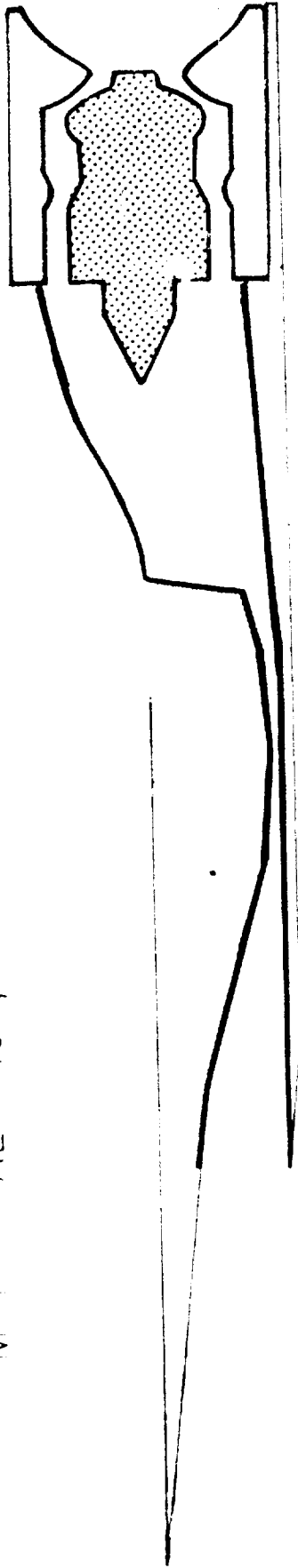
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ENGINE CONCEPTS

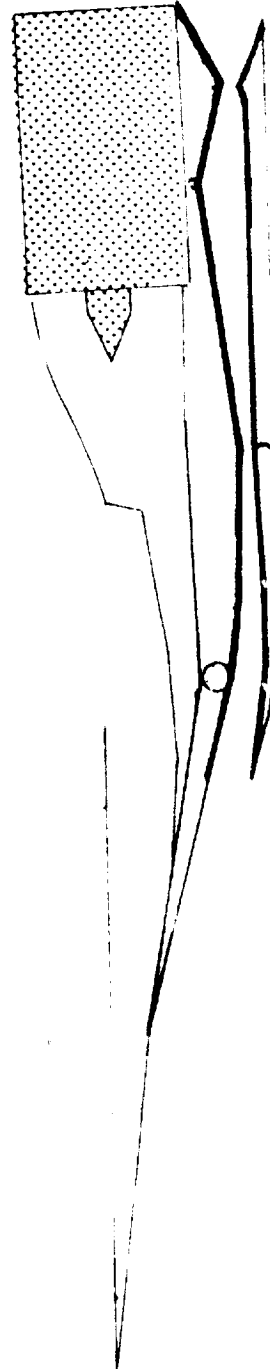
M = 7 ALT = 107,600 FT



COOLED AREA = 825 FT²

$\Phi = 1.6$

INTEGRATED TURBORAMJET



COOLED AREA = 300 FT²

$\Phi = 1.0$

SEPARATE TURBOJET - RAMJET

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1. A low cost, high temperature material
2. A low cost, high temperature material
3. A low cost, high temperature material

11

4. Development of a high temperature material
5. Development of a high temperature material

6. Development of a high temperature material
7. Development of a high temperature material

8. Development of a high temperature material
9. Development of a high temperature material

10. Development of a high temperature material
11. Development of a high temperature material

15

APPENDIX III

THESETH PROPOSITION FOR LH₂ TANKS

40

By: T. Robert Jackson

Presented at AIRCRAFT ENGINE MATERIALS COMMITTEE

on April 23, 1969

INTRODUCTION

1. Recent studies of H₂ show H₂ an efficient fuel.
2. However, 5 times the volume of JP fuel results.
3. Consequently large surface areas need protection.
4. Structure mass fraction required is same as today.
5. But, ΔT is 2000°F instead of say 300°F for SST.
6. So low weight TPS with severe environment are required.
7. I will discuss TPS in detail - however, subjects relating to structure such as integral or non integral tanks will not be discussed.
8. Let's first review requirements of a TPS

Figure 1 - A LH₂ Tank Thermal Problem

1. Prevent excess heating of fuel at low weight
2. Prevent excess cryopumping through unsealed outer surface - leaks of prevent dry condensed transports are important.
3. Provide inert space around tanks

Figure 2 - LH₂ Tank Thermal Protection Systems

1. Evacuated
2. Gas purged

Figure 3 - Multiwall Structural Model

1. Evacuated T.P.S.
2. Vacuum not achieved
3. Need for RMB on sealing thin metals

Figure 4 - Cryoevacuated Foam on Sub-Scale Model

1. Evacuated by condensing of trapped gases
2. Vacuum not achieved at room temperature during fabrication
3. Low use temperature of plastics prevents use of much of the efficient insulation
4. Need for RMB on sealing for reuse and increase temperatures

Figure 5 - Helium Filled Insulation on Tank

1. Fibrous insulation obtained by wire cloth
2. Helium gas due to high conductivity of He and eq. of He usual leak rates

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Figure 6 - Hot Structure Model with CO_2 Purge

1. Conical 3' x 6' of same 41 structure and aluminum tank
2. CO_2 frost cryogenic before flight sublimation inflight
3. Least weight purged concept

Figure 7 - Hypersonic Structures Test Apparatus

1. Shows structural model for calibration and heat shield tests
2. Stand, load system, heaters, and dewars
3. Need LH_2 test capability to prove concepts -- not permitted in present lab.

Figure 8 - CO_2 System Test Results

1. Temperature history of structure and tank wall
2. Two tests to date and each predicted by theory

Figure 9 - Nitrogen Purged Structural Model

1. Less weight than CO_2 system and requires no preflight preparation required with CO_2 system
2. New concept in early stages of development
3. Offers operational and cost advantages, but heavier than CO_2
4. New for testing with LH_2

Figure 10 - Research Summary of LH_2 Tank T.P.S.

1. Liquid hydrogen testing
2. Determine least metal thickness that can be reliably sealed for various alloys
3. Determine means of reliably sealing plastics
4. Increase maximum use temperature of plastics
5. Determine what insulation prevents liquid nitrogen flow but permits non destructive outgassing during high heating rates.
6. Perform in-depth study of various thermal protection systems including tank wall cooling

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A LIQUID HYDROGEN TANK THERMAL PROBLEM

CRYOGENIC PUMPING

UNSEALED STRUCTURE

INSULATION

CONDENSING AIR

CIRCULATING AIR

HEAT

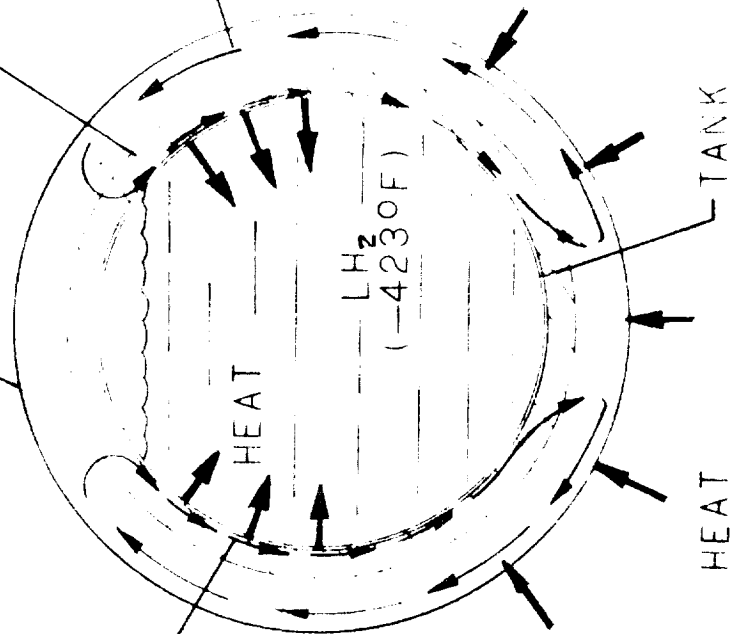
LH₂
(-423°F)

TANK

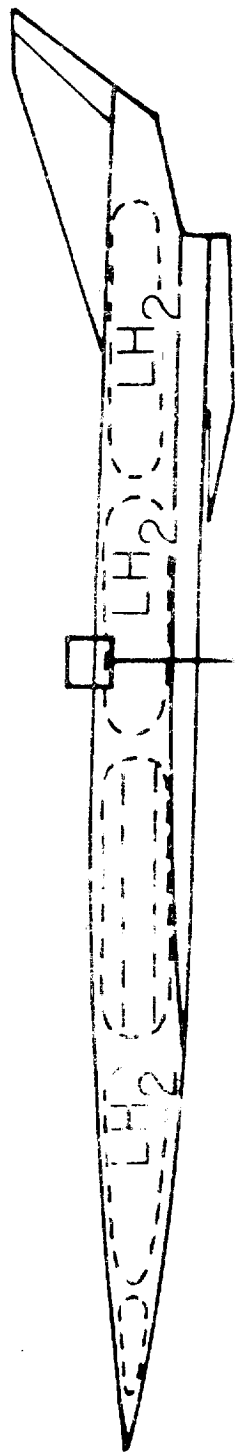
HEAT

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LIQUID HYDROGEN TANKS



EVACUATED PURGED

UNSEALED STRUCTURE

INSULATION

PURGE GAS

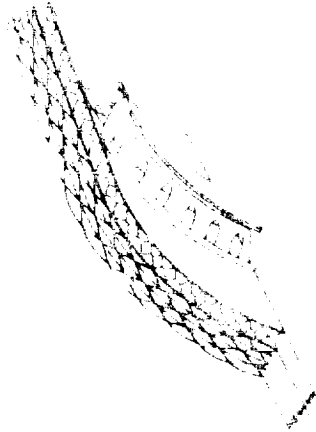
SEALED
SURFACE

Q_f

FUEL HEAT LOAD, Q_f

TANK WALL
EVACUATED CONTAINER

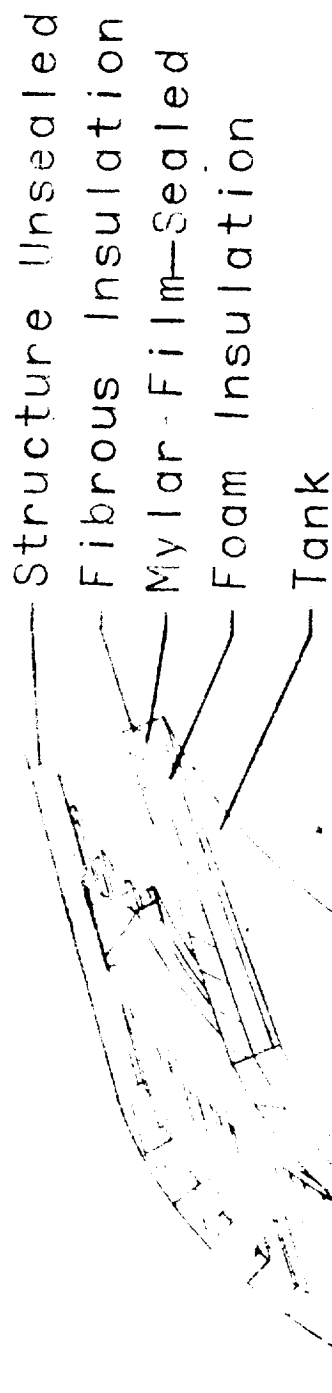
MULTIWALL STRUCTURAL MODEL



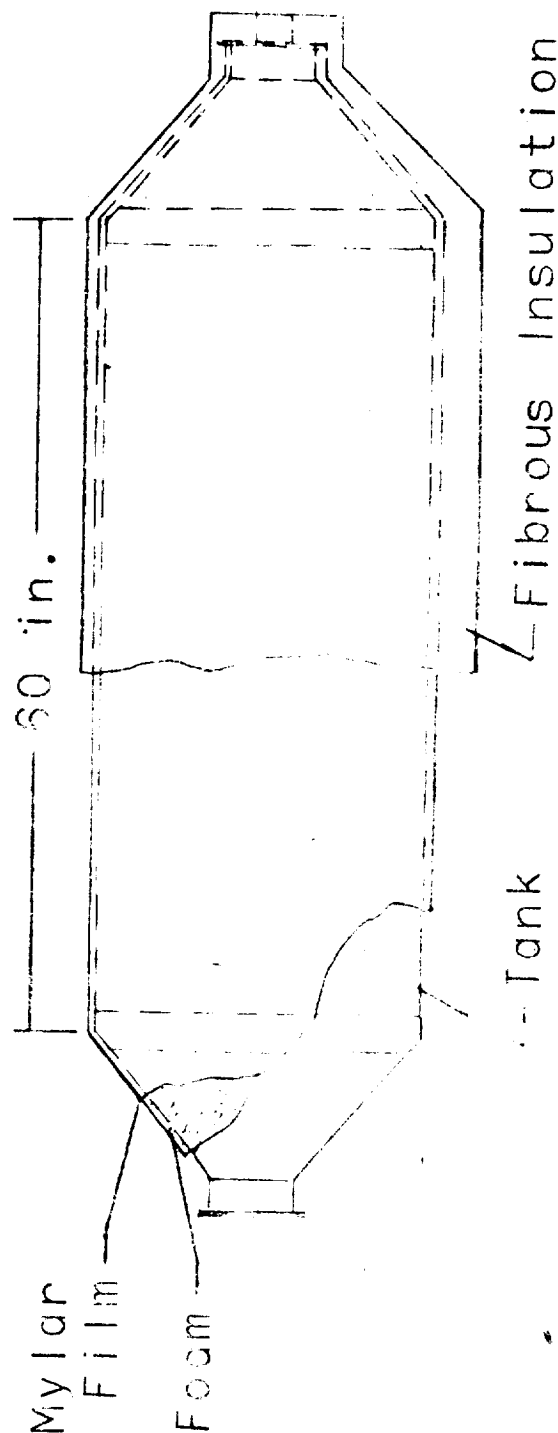
LOAD-BEARING STRUCTURE
FLUCTUATION FOR LOAD STRESS

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CRYOEVACUATED FOAM ON SUBSCALE TANK
TITANIUM ALLOY USAF - GD/C



(11)

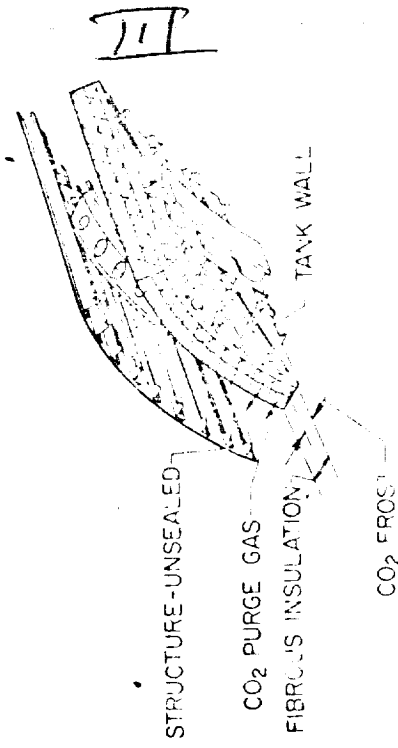


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HOT STRUCTURAL MODEL WITH NONINTEGRAL TANKAGE AND CO₂ PURGE SYSTEM



UNIT FOR DETECTING, LOCATING, APPARATUS FOR RESERVING
OF STRUCTURES OR PERSONAL VEHICLES

Radionuclide
Detector

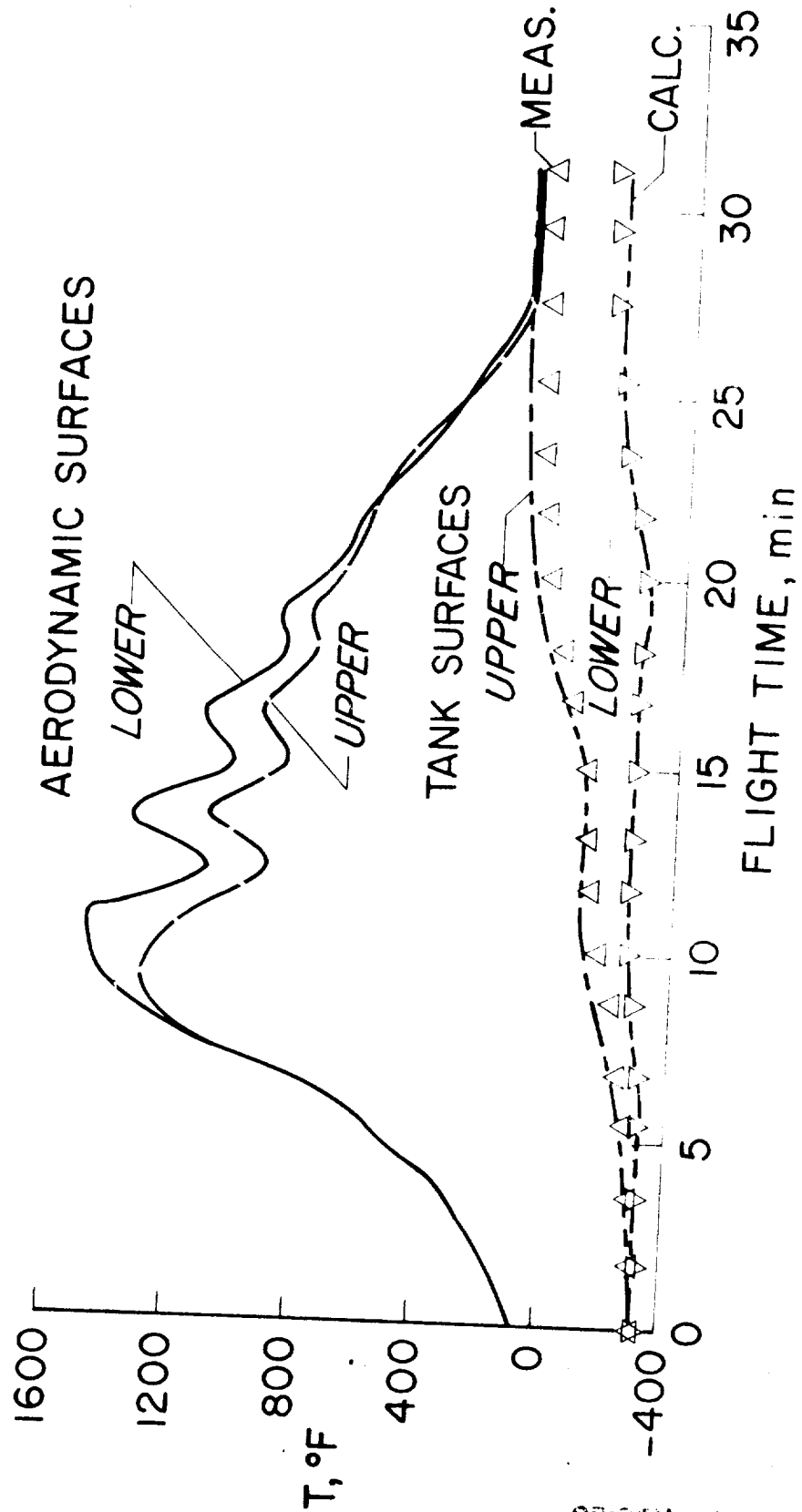
Radionuclide
Detector

Radionuclide
Detector

Radionuclide
Detector

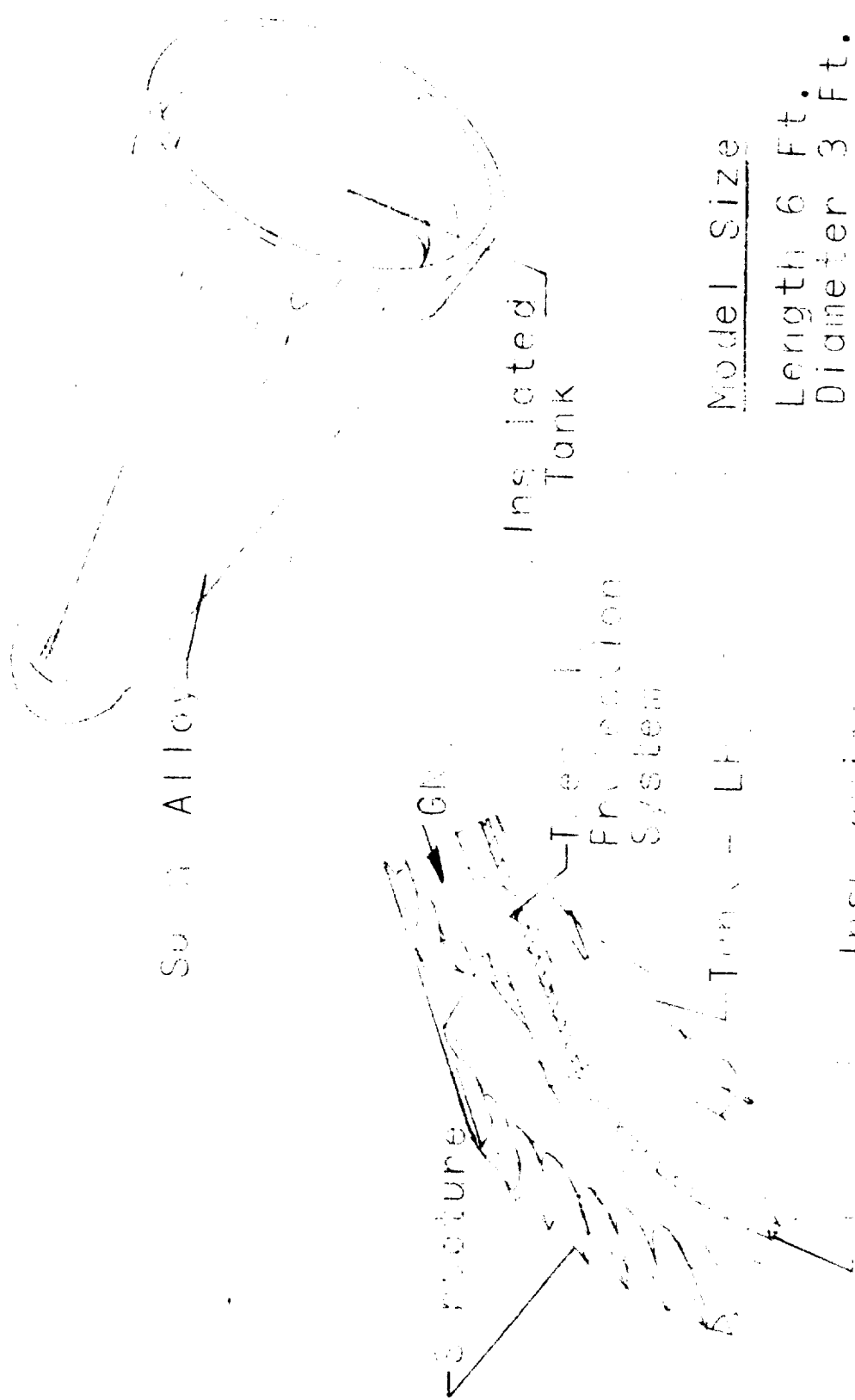
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CO₂ SYSTEM TEST RESULTS



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FITTED PURGE STRUCTURAL MODEL WITH LEADED PANEL STRUCTURE



Model Size

Length 6 Ft.
Diameter 3 Ft.

RESEARCH SUMMARY
FOR LH₂ TANK THERMAL PROTECTION

Liquid hydrogen testing

Determine least metal thickness that can be reliably sealed for various alloys

Determine means of reliably sealing plastics

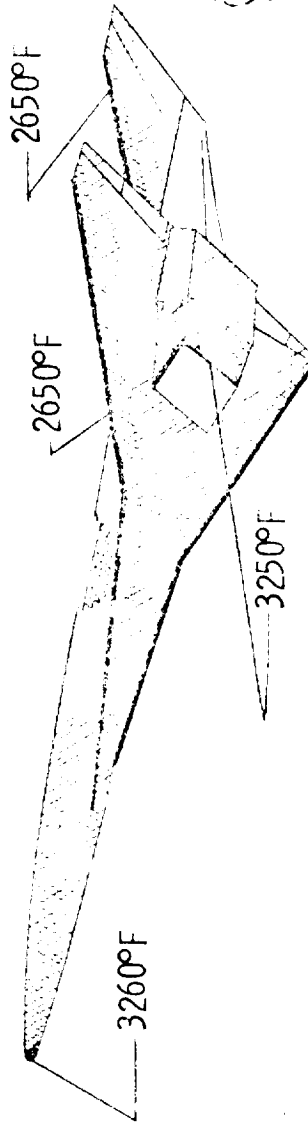
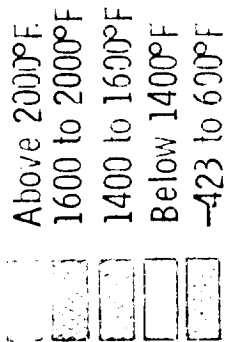
Increase maximum use temperature of plastics

Determine what insulation prevents liquid nitrogen flow but permits non destructive outgassing during high heating rates

Perform in-depth study of various thermal protection systems including tank wall cooling

HYPERSONIC CRUISE AIRCRAFT STRUCTURE ENVIRONMENTS

Equilibrium Skin Temperatures



APPENDIX IV
B.A. STEIN

Environmental Conditions

Application	Materials	Temperatures	Exposure Times	Other Conditions
Primary Structure	Superalloys, Composites	Below 1600°F	>5000 hours	Air, 8 torr
Heat Shield	Superalloys, Composites	1600 to 2000°F	>5000 hours	Air, 8 torr
Leading Edge and Heat Shield	Coated Refractory Metal, Graphite Composite	2000 to 3100°F	50 hours	Air, 8 torr
Nose Cap and Leading Edge	Graphite Composite, Ceramic Composite	3100 to 4000°F	5 hours	Air, 8 torr
Tankage	Titanium Alloy, Stainless Steels	-423 to 600°F	>5000 hours	LH ₂ inside He or CO ₂ outside

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NON-REFURBISHABLE SUPERALLOY PRIMARY STRUCTURE AND HEAT SHIELD MATERIALS

Outline of Test Program

Purpose: Determine usefulness of existing or newly developed thin sheet materials in simulated hypersonic aircraft environments.

Materials: In 625, In 718, Hast X, L-605, Haynes 188, Rene 41, TD Ni-20Cr

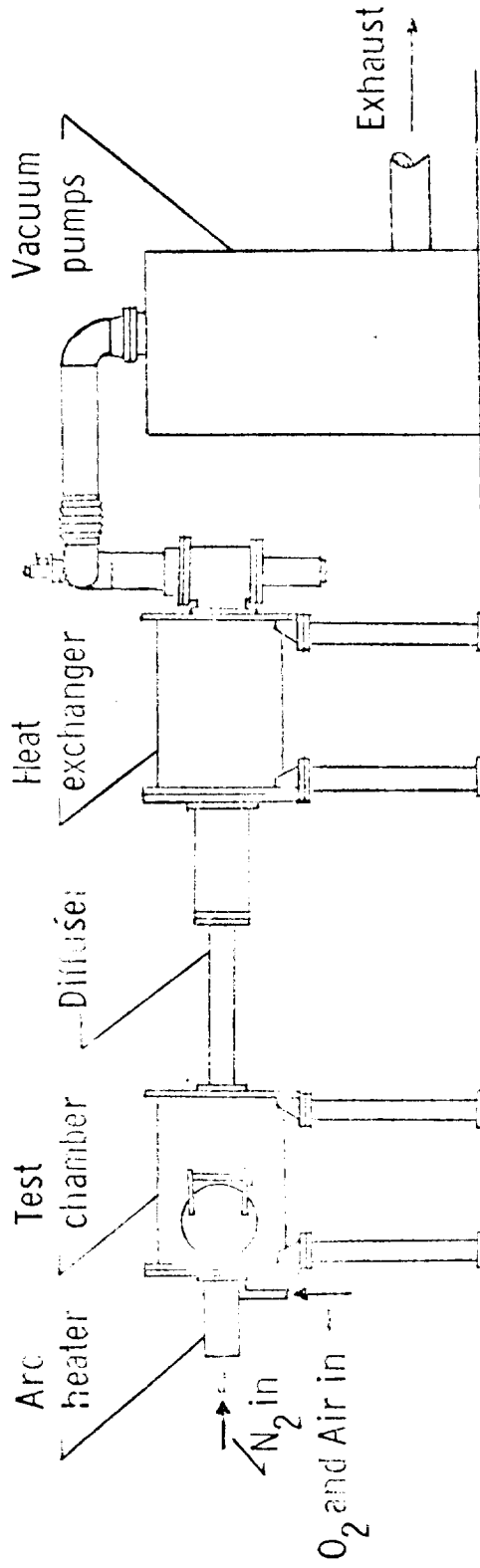
Specimens: Tensile strips and oxidation coupons; 0.010 and 0.020 inch thick

Equipment and Test Parameters:

EQUIPMENT	TEST PARAMETERS			
	Pressure, torr	Flow Stress, ksi	Cycling	Temperature, °F
Static Environmental Test System	8	None ≤ 50	No	1400 1800
Vacuum and Ambient Ovens	8 760	None 0	No	1400 1800
Static Environmental Flight Cycling Chamber	Cyclic, 760 to 8	None 0	Yes	-50 to 1800
Hypersonic Materials Environmental Test System	5 to 10	High velocity	Yes	1400 1600 1800
				Testing in progress
				Testing in progress
				Under construction
				Calibration tests

HYPERSONIC MATERIALS ENVIRONMENTAL TEST SYSTEM

Equipment



Ranges of Controlled Testing Parameters

Specimen: Curved oxidation specimen or tensile strip

Temperature: 1200°F to 5000°F

Static Pressure: 1 to 10 torr

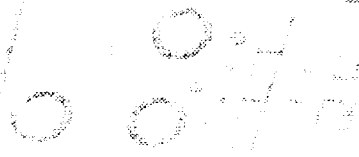
Load on Tensile Strip: 0 to 500 lb

Test Gas: High velocity air or inert gas

Gas Flow Rate: 0.01 lb/s

Test Duration: 1 to 8 hours per run for long cumulative exposure times on specimens

UNPERSO N MATERIALS ENVIRONMENTAL TEST SYSTEM



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CURVED OXIDATION SPECIMEN IN HIGH VELOCITY AIRSTREAM
Magnation Line at 1800°F

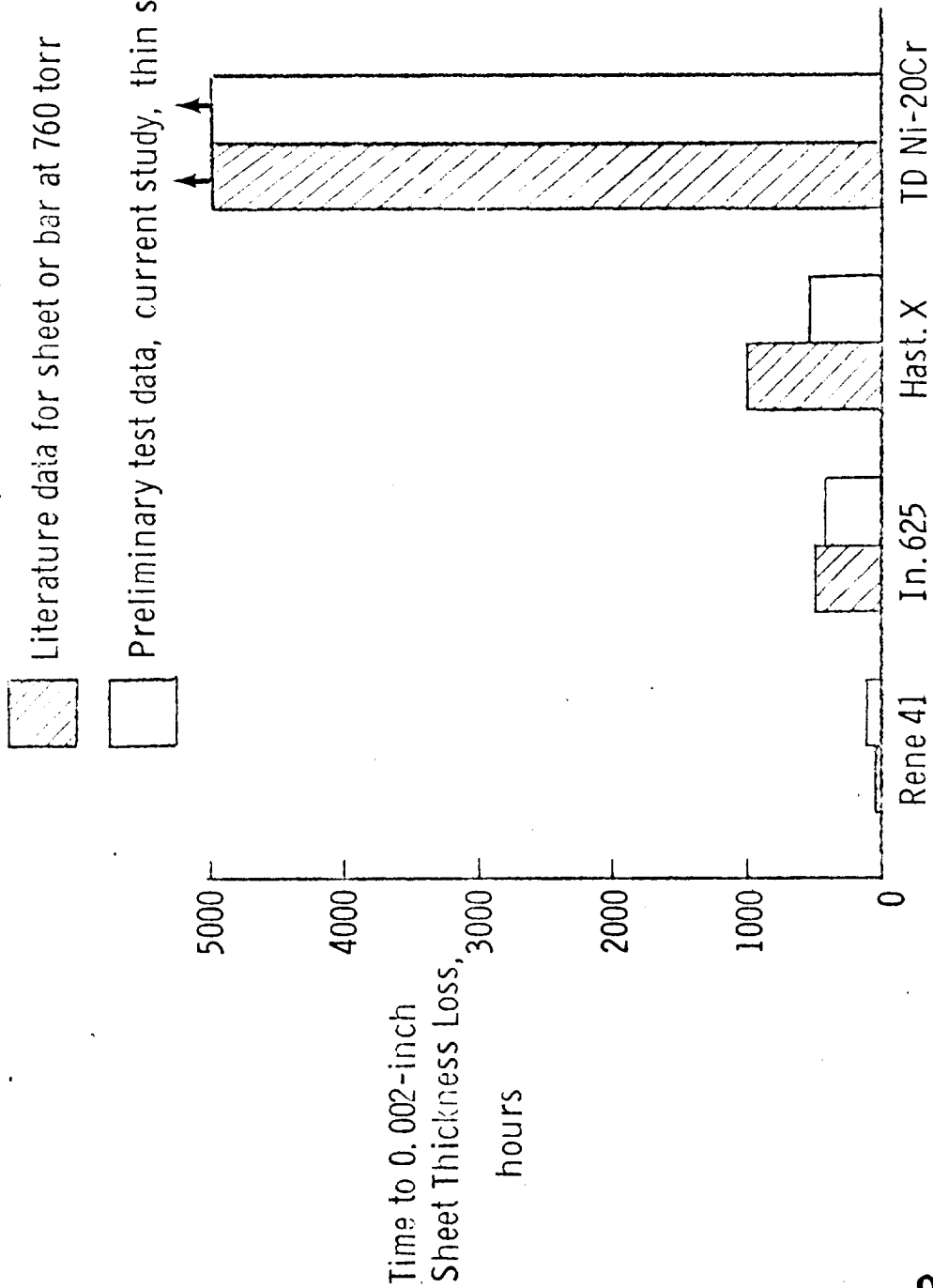
Slide 5

B. Stein

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OXIDATION OF CANDIDATE MATERIALS FOR NON-REFURBISHABLE HEAT SHIELDS

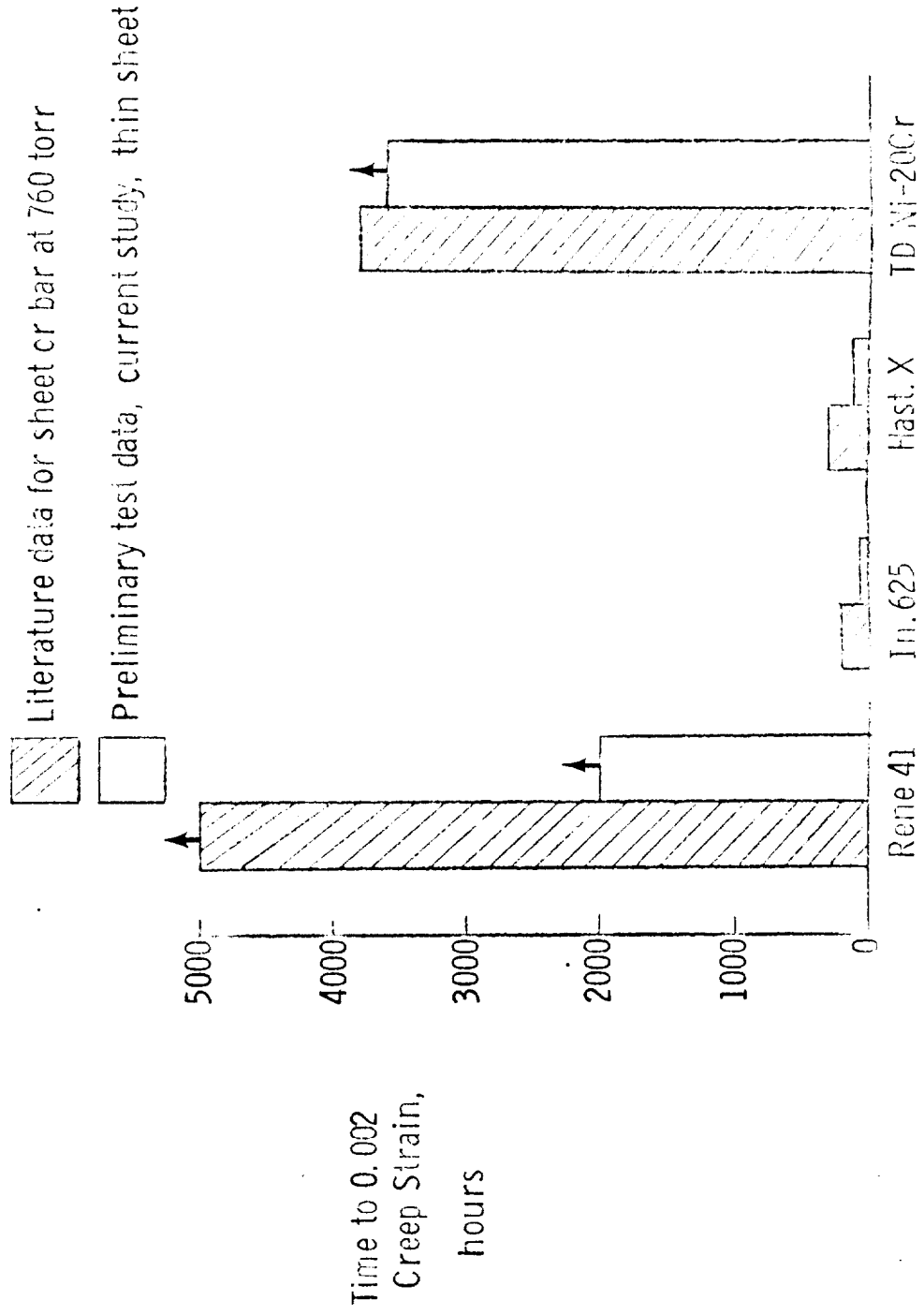
Continuous tests of Coupons at 1800°F, 8 torr



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CREEP OF CANDIDATE MATERIALS FOR PRIMARY STRUCTURES OF HYPERSONIC AIRCRAFT

Continuous tests at 1400°F, 10ksi, in 8 torr air



Time to 0.002
Creep Strain,
hours

12

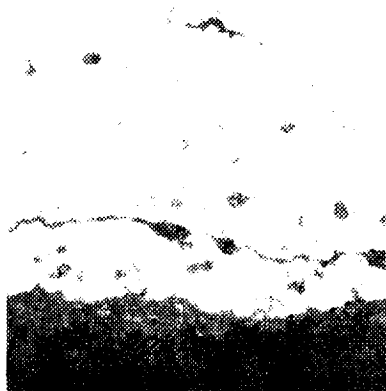
OXIDATION OF TD Ni-20Cr (Ni - 20Cr - 2ThG₂)

After 100 hours at 1800°F in air at 760 torr

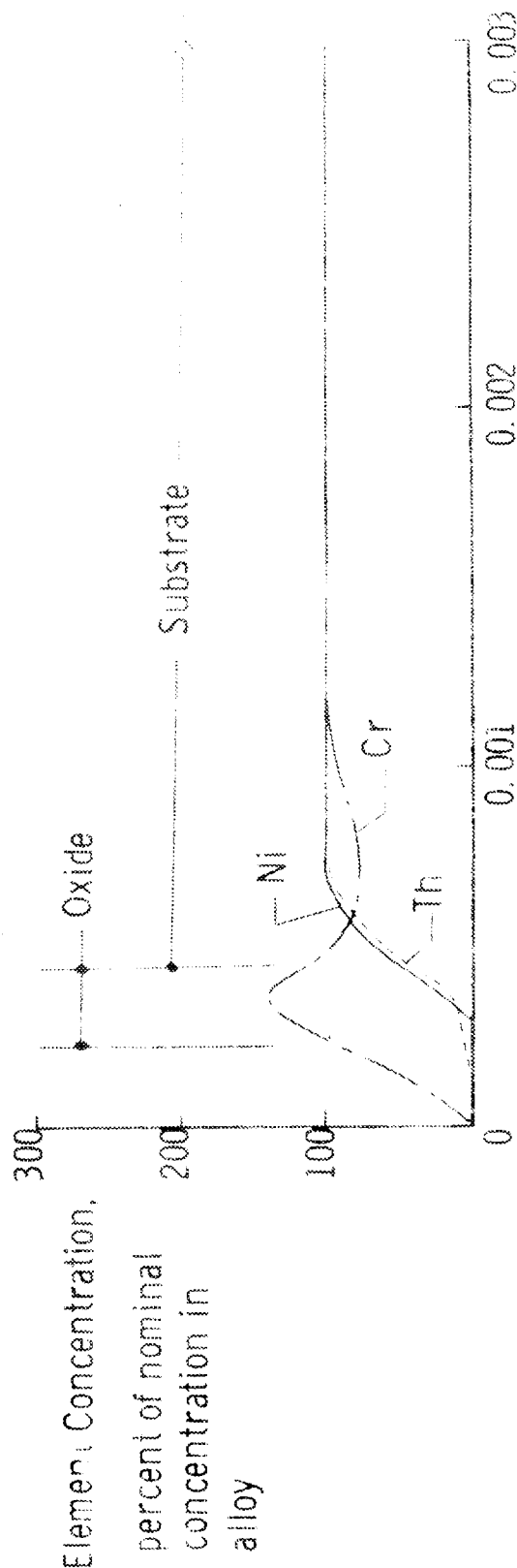


Unetched

0.001 inch



Etched



Distance perpendicular to specimen surface from reference point, inches

Slide 8

R. Stein

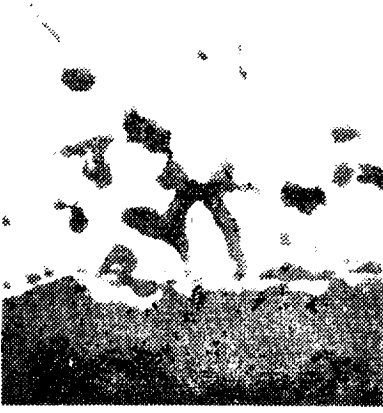
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OXIDATION OF RENE 41 (Ni - 19Cr - 11Co - 10Mo - 3Ti - 1.5Al)

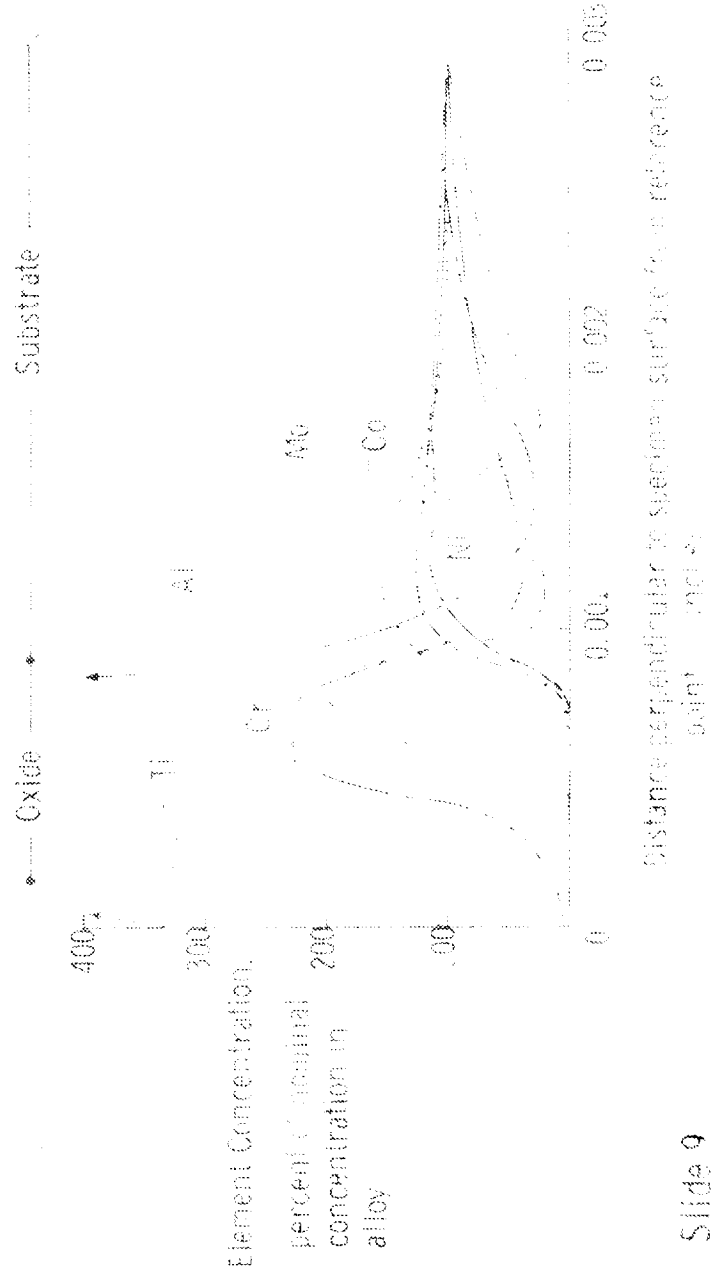
After 100 hours at 1800°F in air at 760 torr



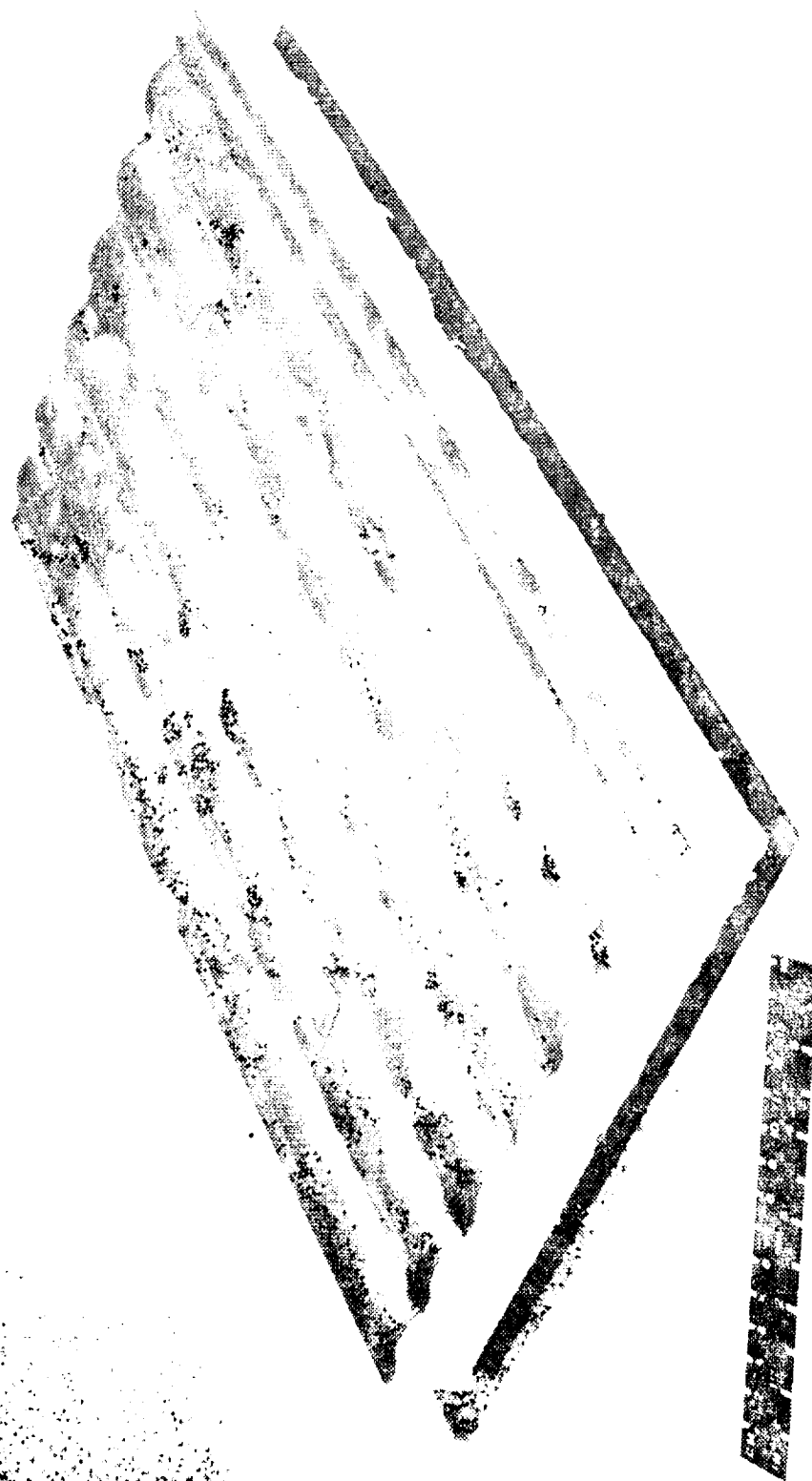
Unetched



Etched



Al-Sn-Mo COA, D FLAT TANTALUM ALLOY HEAT SHIELD
Attached to Insulated Superalloy Substructure

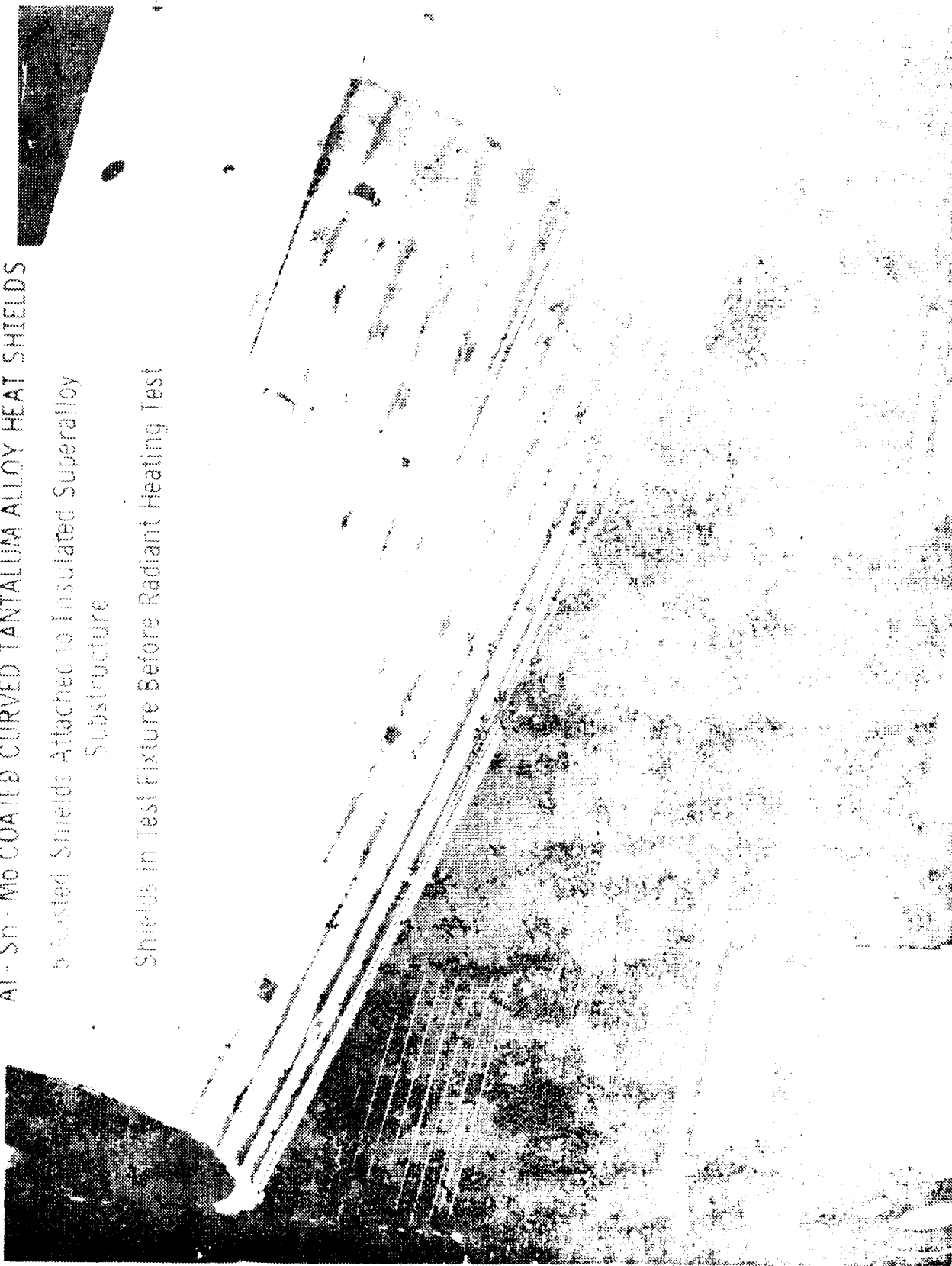


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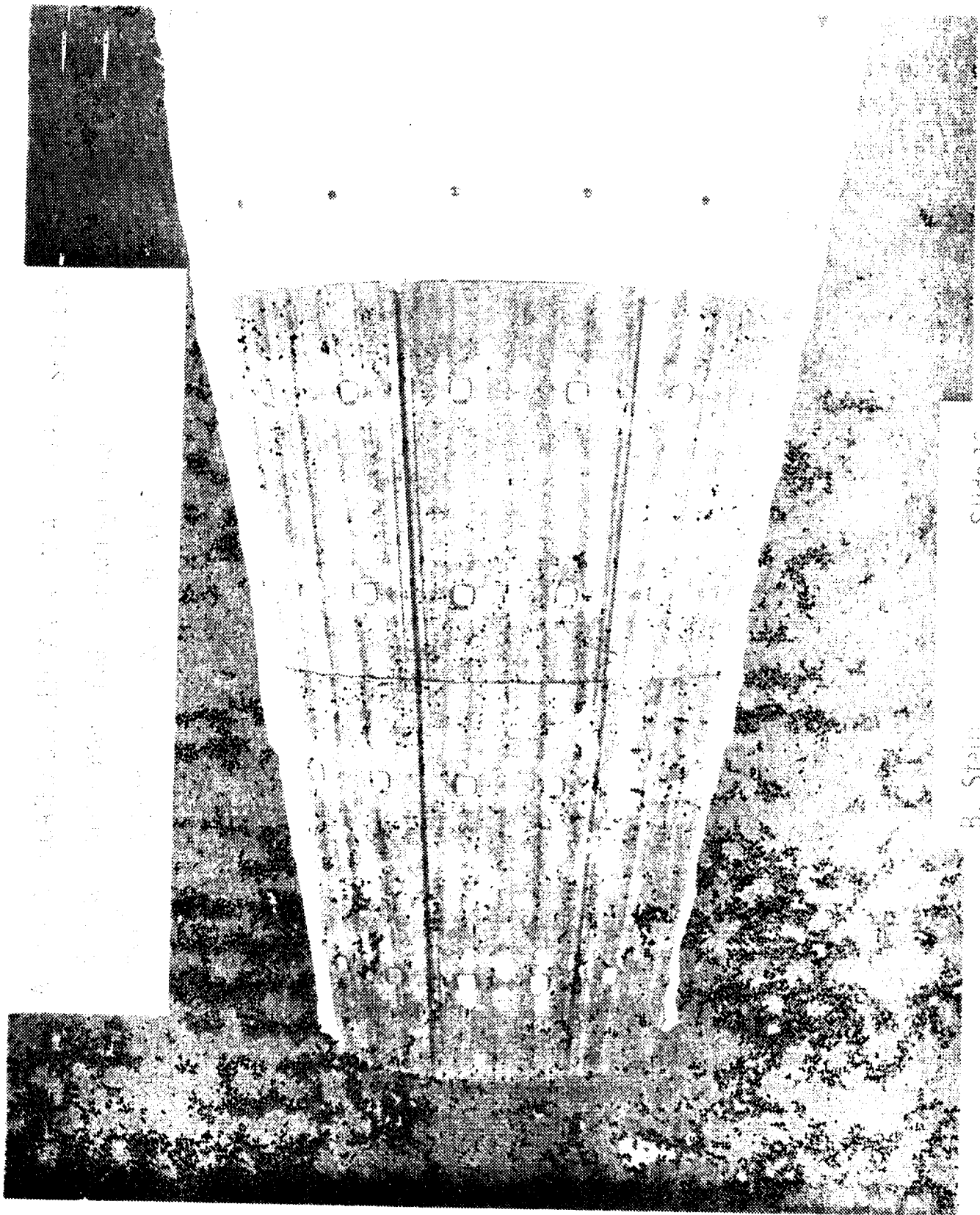
Al-Sn-Mo COATED CURVED TANTALUM ALLOY HEAT SHIELDS

6 Rusted Shields Attached to Insulated Superalloy Substructure

Shields in Test Fixture Before Radiant Heating Test



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Slide 12

B. Stein

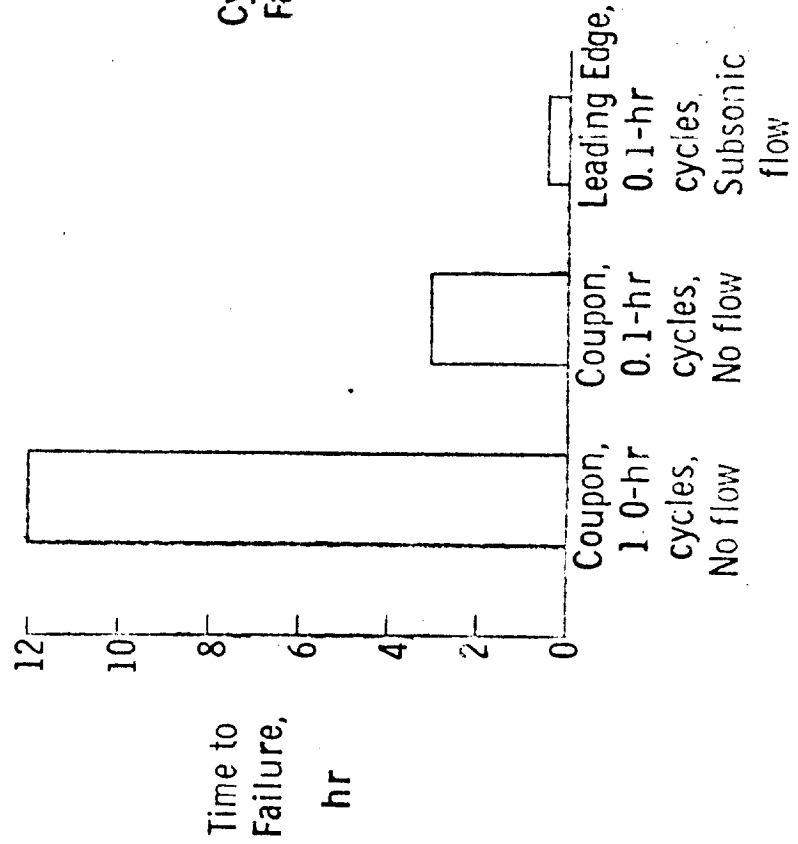
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COATING PERFORMANCE ON TANTALUM ALLOY COUPONS, LEADING EDGES, AND HEAT SHIELDS

Sn - Al - Mo Coating on Ta-10W Sheet

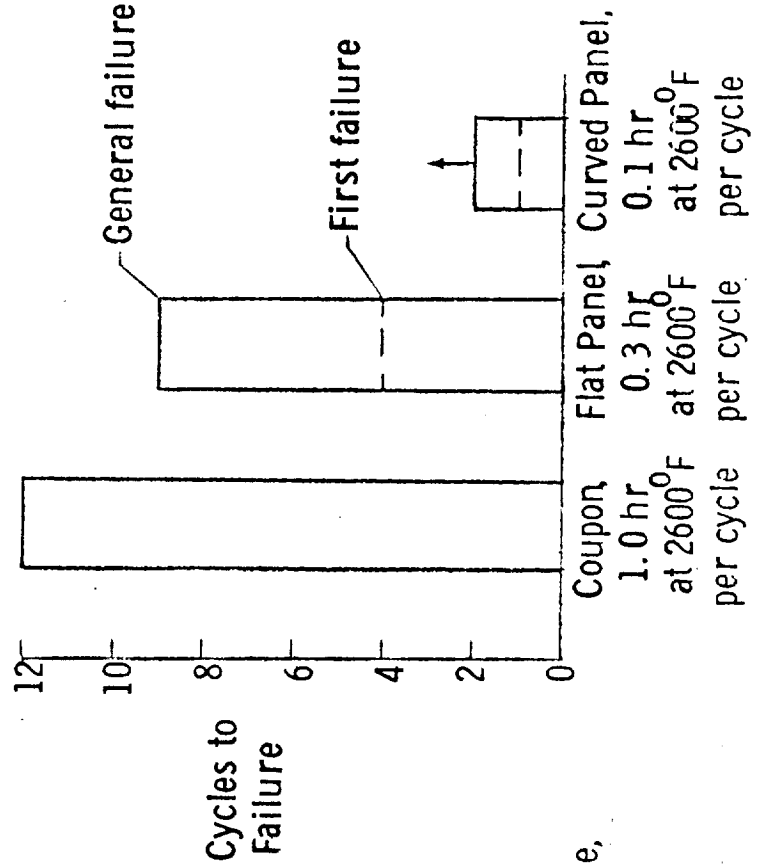
Effect of Cycling Time and Air Flow,

2600°F



Effect of Specimen Size and Complexity

1-hr static air test cycles, 2600°F max.



HYPersonic RESEARCH ENGINE PROJECT

OBJECTIVES

PROVIDE A FOCAL POINT FOR RESEARCH:

APPLICATION AND INTEGRATION OF COMPONENT RESEARCH RESULTS

GUIDE AND STIMULATE RESEARCH:

CONTINUING RESEARCH ON HYPERSONIC AIRBREATHING PROPULSION TECHNOLOGY

GENERATE FACTUAL ENGINE DATA:

BASIS FOR HYPERSONIC PROPULSION DECISION AND DESIGN

DETERMINE SUITABILITY OF TECHNIQUES AND FACILITIES:

HYPersonic RESEARCH ENGINE DEVELOPMENT

APPRAISE NEEDS AND REQUIREMENTS:

HYPersonic PROPULSION
RESEARCH AND DEVELOPMENT FACILITIES AND TECHNIQUES

APPENDIX V

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Tom Bonner

Ernest Mackley

PROJECT PHASE PLAN

FOR

HYPERSOONIC RESEARCH ENGINE

PHASE 1 - CONCEPT DEFINITION
PRELIMINARY DESIGN
DEVELOPMENT PLANNING

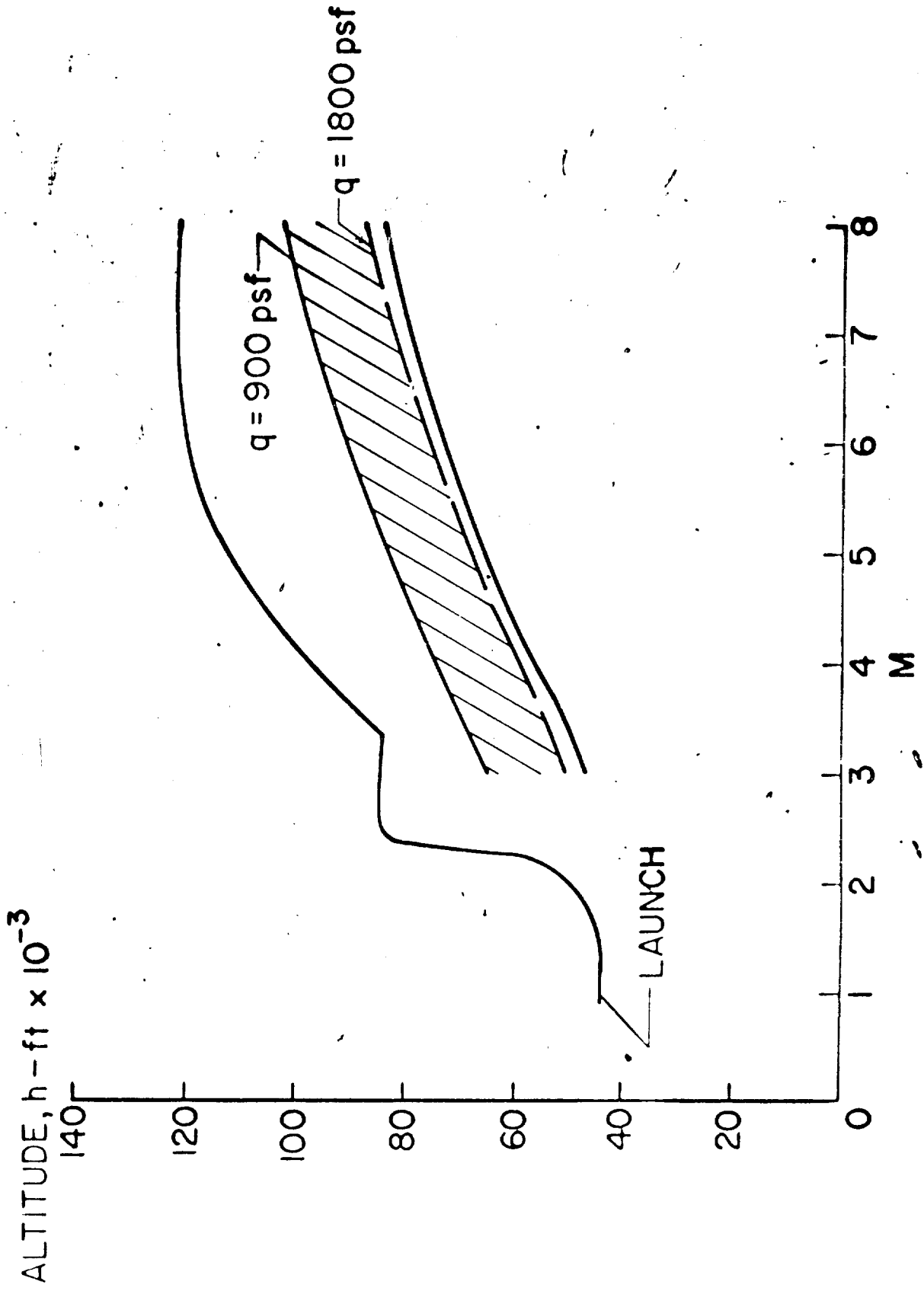
COMPLETED

PHASE 2 - COMPONENT DEVELOPMENT

AEROTHERMODYNAMIC
STRUCTURES AND FABRICATION
INTEGRATED DEVELOPMENT

AEROTHERMODYNAMIC INTEGRATION MODEL
STRUCTURES ASSEMBLY MODEL

MACH NUMBER-ALTITUDE PROFILE ENVELOPE OF THE X-15-2



6

HYPERSONIC RESEARCH ENGINE

MANUFACTURING PROCESS

HASTELLOY-X OFFSET FIN - PLATE CONSTRUCTION AND FORGINGS

ELECTROSHAPE FORMING

CHEM MILLING

ELECTRIC DISCHARGE MACHINING

INERT ATMOSPHERE BRAZING

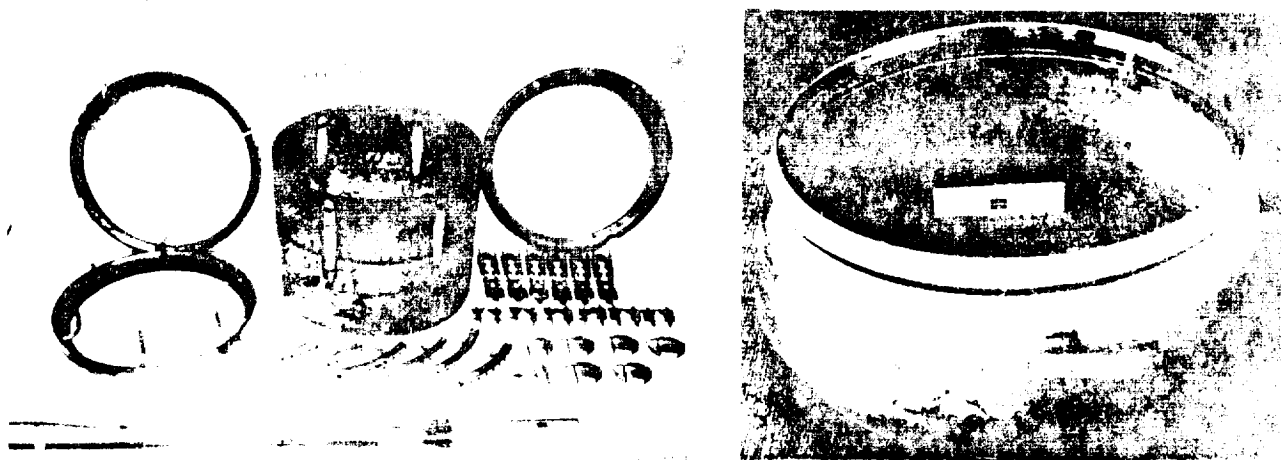
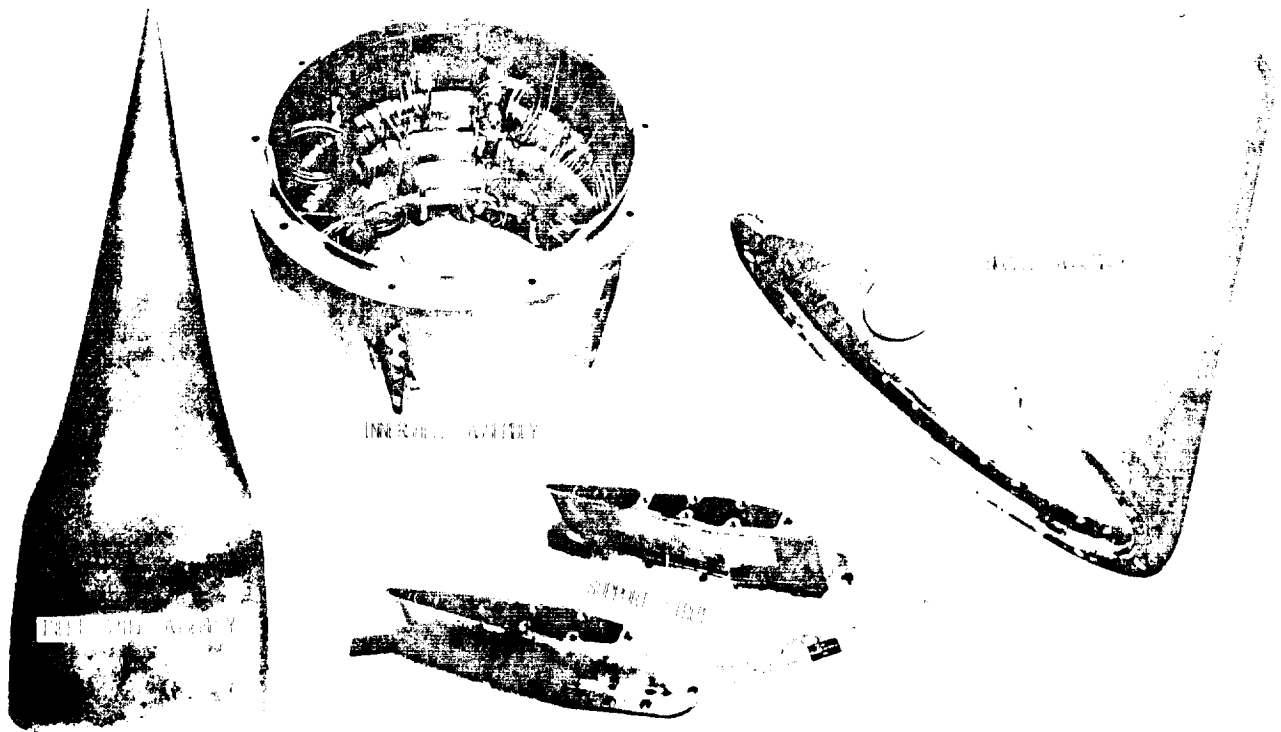
HIGH GOLD CONTENT BRAZE ALLOYS - 4 CYCLES
-CREEP FORMING

NON DESTRUCTIVE TESTING

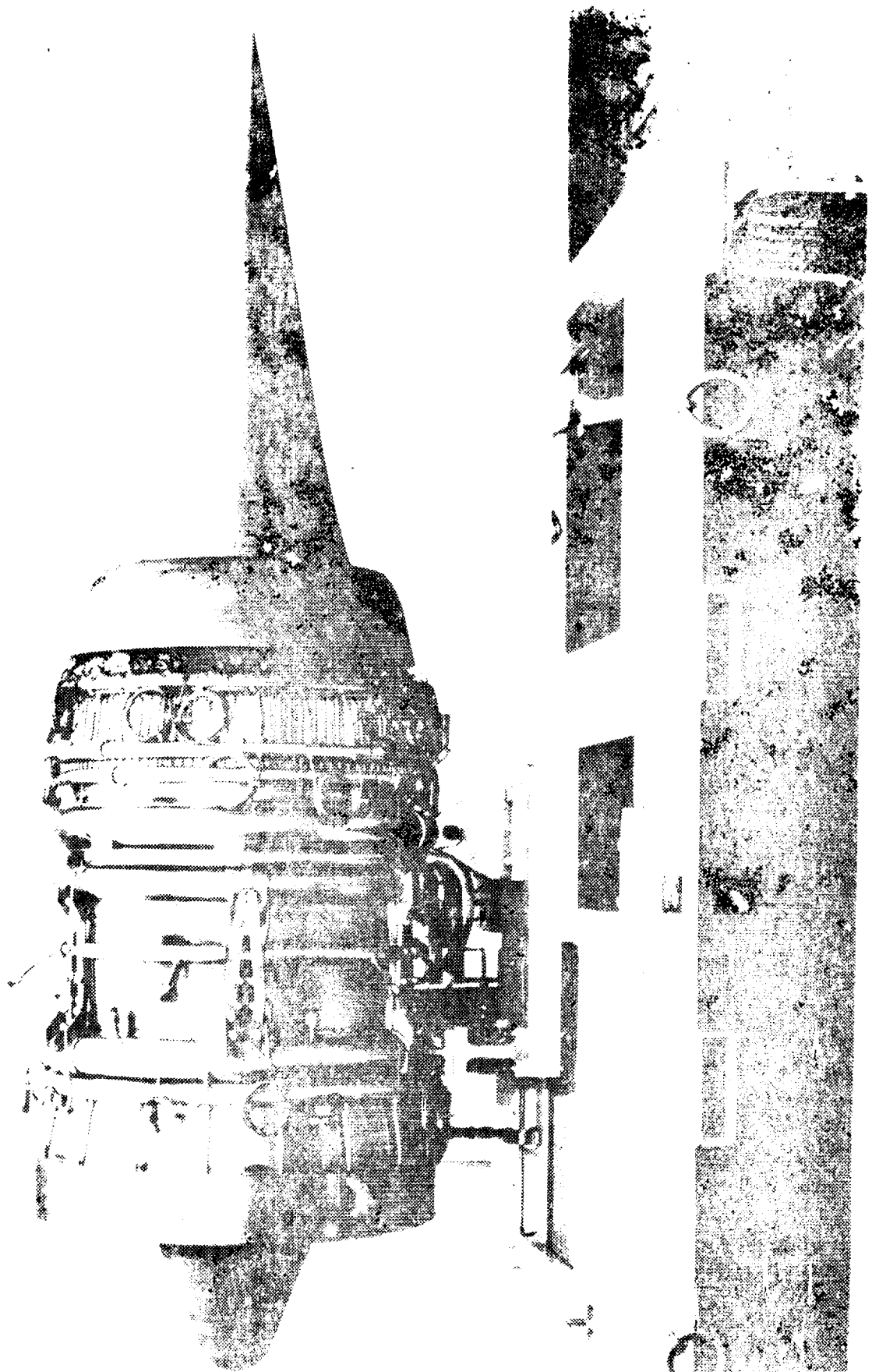
-X-RAY FOR FIN PLUGGING

-CEMATIC STRESS COAT FOR BRAZE STRENGTH

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APPENDIX VI

14 April 1971

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NOT FOR JET ENGINES

SUB-Panel on NDT & LIFE PREDICTION

Introduction

As a result of expanding activity during the last several years, the identification of physical methods which might be the basis for NDT techniques has outstripped the applications of these techniques to jet engines. Many recent advances in familiar NDT approaches have not yet been adequately applied to the engine inspection problems. These include: television x-ray, laser assisted ultrasonics, electronic data processing and pattern recognition, and pulsed eddy currents. In addition, some of the newer techniques which have received little evaluation for jet engines are: holography, thermography, neutron radiography, magnetoabsorption and kryptonation techniques.

Near future overall emphasis should probably be on exploring the application of basic physical methods to the configurations and service regimes/environments which will be experienced in jet engines. This will require acquisition of correlations between the "swing of the needle" and behavior of components in simulation tests or service performance. There is a great need for this correlation data and for additional knowledge which can be obtained about the physics of the failures which occur in service to provide focus to activities searching for new physical methods or their development into practical NDT tools.

A second overall factor for considerable attention will be the introduction of automated NDT techniques in order to both keep costs within reason and to reduce the factor of human error. The latter might otherwise become a limiting problem as the expanding use of sophisticated techniques outweighs the availability of highly trained people, and the complexity of the required data increases.

Correlation Studies

The development of nondestructive methods beyond initial laboratory research on possible new physical methods can rapidly become quite difficult indeed if it does not benefit from extensive feedback of the knowledge of physics of failure under real service conditions, and the opportunity to correlate NDT indications with the actual behavior of parts. The latter one, of course, become quite expensive and it becomes necessary for the "push-back" on hardware development or test programs. Research activities offer to try out their new "breadboard" capabilities on hardware items which will be subjected to simulation or service testing. These activities must expect to pay the cost of accomplishing this in the hope of obtaining useful feedback in the form of valid correlations. Examples of areas where the convergence of needs with possibly applicable NDT approaches suggest such an approach are:

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- d. inspection of coatings
- e. applications of acoustical analysis
- f. wall thickness measurements in cooled turbine blades
- g. detection of cracks in titanium
- h. inspection of electron beam weld repairs
- i. inspection of diffusion bonded composite structures
- j. improved automated inspection of billets for nonmetallic inclusions
- k. detection of deterioration of installed bearings

Fundamental Knowledge

Although overall emphasis at this time should be on application and evaluation of existing physical methods there are many areas where additional fundamental knowledge is required, or potential inspection problems where no suitable physical methods appear to be available or recognized. There is, of course, the never-ending desire to detect and characterize smaller and smaller cracks and flaws. Beyond this, some examples of fundamental topics requiring attention are:

- a. detection of fatigue damage prior to appearance of a crack
- b. suitable methods for detection of over temperature "burning" in hot components
- c. strength of adhesive bonds
- d. possible remnant (stress corrosion) effects of penetrants.

Pattern Recognition

Another area where considerable long-range activity is warranted is the general subject of pattern recognition. For example, the use of vidicon techniques with filters to provide improved readout and pattern recognition in radiography is being developed for a variety of applications such as the inspection of graphite bodies, but has not yet been applied to engine problems. A wealth of information can be obtained from ultrasonic methods, but the exploration of the possibilities of these techniques is in its infancy largely due to the problems of handling the mass and complexity of the signals. Direct electronic readout can prove to be very useful here.

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APPENDIX VII

16 April 1952

FATIGUE LIFE PREDICTION IN JET ENGINES

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1. The use of analytical techniques to predict the fatigue response of jet engines is still very much in its infancy at the present time. The standard approach used by engine manufacturers to verify their engine design may be summarized in the following steps:

a. The proposed design is subjected to as complete a stress-analysis as modern simulation techniques will allow:

b. The stress data obtained from (a) is used in conjunction with materials S/N curves, Goodman diagrams, and elementary cumulative damage laws to arrive at the first estimate of the fatigue response. This estimate is little more than an educated guess.

c. Engine components considered critical in fatigue (e.g. blades) are bench tested to determine the fatigue endurance limit and to demonstrate adequate life. These tests are also used to confirm the stress data obtained in (a).

d. Full scale simulated service tests are finally run on the completed engine design. It will be noted that the technique relies heavily on after-the-fact testing to "prove" the fatigue design. Prior prediction plays a relatively minor role.

2. This approach has been reasonably successful in the past but new systems coming into service and being planned make it necessary that a more analytical technique be adopted. For one thing, the longer design lives of many of the new systems are making it increasingly costly (in terms of both dollars and time) to run the type of tests that have been run in the past.

3. It is obvious that the problem of fatigue prediction in a system and environment as complicated as that of a jet engine is a very difficult task. In fact existing techniques are incapable of doing this successfully. In order to improve this situation a considerable effort is going to be necessary in the future. The following suggestions are made in connection with this effort:

a. It is essential that the operating environment be defined more accurately. More thought must be given to ways of recording stresses, temperatures, times etc from operational engines as well as from test set ups.

b. The information obtained from (a) could be used to refine and screen existing theories of cumulative damage. The availability of adequate environmental information would make it possible to assess how well current cumulative damage theories predict the component lives that are encountered in test set ups or service experience.

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c. Thought should be given to the feasibility of adapting the reliability concepts, developed in recent years for flight structures, to engines. These techniques which relate time to first failure to both fleet size and time to mean failure have proven very successful. (Ref AFML-TR-69-65). However the more severe environment of an engine would complicate this process.

d. The greatest shortcoming at the present time is our lack of understanding of interaction effects taking place e.g. fatigue modified by simultaneous creep. Unless current elementary cumulative damage laws prove to be unexpectedly adequate, a great amount of study, both phenomenological and fundamental, may be needed in this area.

4. There are a number of people and groups throughout the US who are concerned with various aspects of these problems. The engine manufacturers are certainly looking at some of these aspects usually though at a level closely tied to production problems. One of the first things that needs to be done is a survey to establish the level and direction of current efforts.

5. It is absolutely necessary to accumulate actual service history data on engines such as recordings of stress and strain, strain rates, temperature and temperature gradients, and heating rates. Such data are needed for intelligent assessment of life predictions of critical fatigue sensitive locations. This knowledge must be coupled with relevant system and component static and dynamic developmental tests in order to apply current reliability techniques.

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APPENDIX VIII

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May 20, 1969

SUB PANEL ON SUPERALLOYS RECOMMENDATIONS

The following recommendations are based upon discussion by the Sub Panel at Sterling Forest and Seattle, upon communications between members and the chairman, and upon final comments at Langley Field:

1. Powder Metallurgy

More research and development is recommended on powder metallurgy aimed at improvements in sintered and hot pressed alloys. Consolidation of powders atomized from prealloyed melts has much to offer as regards composition modification, obtaining fine grainsize and achieving different forms or shapes more economically.

2. Disk and Shaft Materials

More R & D on disk and shaft materials for operation in the temperature range of 900-1400 F is recommended. Substantial improvements in strength (e.g., torsional fatigue strength) at intermediate temperatures could be of great significance in contributing to performance and weight saving.

3. Hot Corrosion & Oxidation

Greater effort on the study of the mechanism of response of superalloys to corroding environments is indicated. The ultimate aim should be superalloys of higher temperature capability with improved hot corrosion and oxidation resistance, strength and stability.

4. Directional Solidification

The advantages of directional solidification point up the need for R & D effort on new alloys designed specifically for directional solidification and the evaluation of properties of current alloys when directionally solidified.

5. Superalloy Composites

Superalloy composites, particularly for blading, should get high priority. Refractory fibers in a superalloy matrix have considerable promise of improved high temperature capability.

6. Dispersion Strengthening

Dispersion strengthening as a means of achieving stronger superalloys of higher melting point should continue to be backed with emphasis on optimization of thermomechanical processing of such alloys. The economics of dispersion strengthened alloys should continue to receive attention.

7. Study of Reduced Strength in Thin Walls of Castings

Work designed to understand the problem of reduced strength in the thin walls of conventionally cast superalloy blades is recommended. Effects of casting variables, grain size, and interdendritic spacing versus cast section size are examples of knowledge needed. Comparison with thin walls in wrought and sintered and hot pressed superalloys is suggested.

Submitted by the Sub Panel on Superalloys

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